Chapter 5
Design of Full-Scale SVE and BV Systems

5-1. Introduction

The main objective in designing a full-scale SVE or BV system is to provide a system that will maximize the removal of contaminants from the subsurface in the most efficient and timely manner. In order to achieve this objective, the design team must have a good understanding of the composition and characteristics of the contaminants to be removed, the location of the contaminants in relation to the water table, the characteristics of the soil in the zone of interest, the rate-limiting step in contaminant removal at the site, and the desired airflow rate and flow path to remove the contaminants from the subsurface. These data needs were addressed in Chapter 3.

5-2. SVE and BV Design Strategy

In order to thoroughly and properly design an effective full-scale SVE or BV system, a comprehensive design team must first be called upon. The design team should include the following:

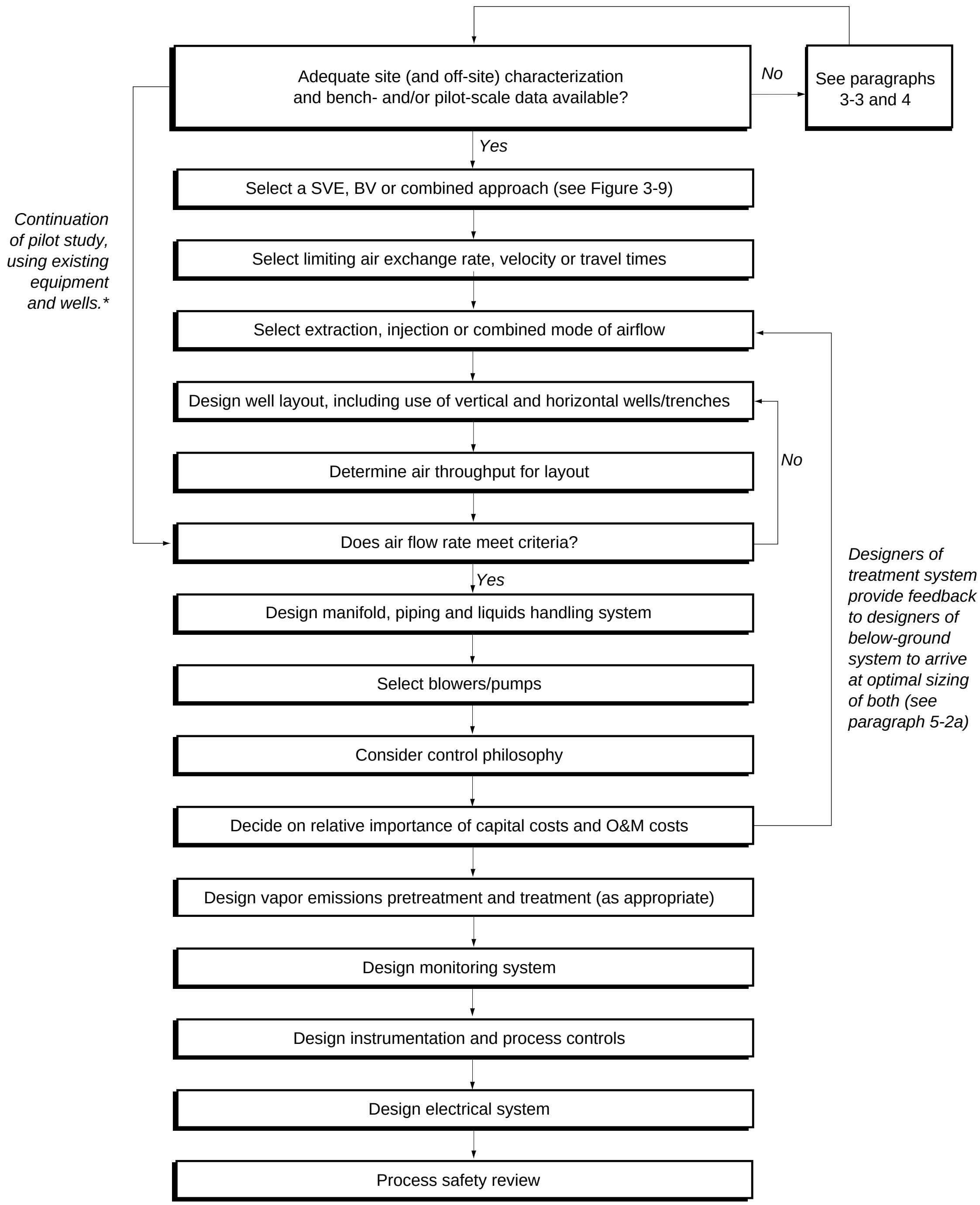
- Environmental/chemical engineer.
- Health and safety specialist.
- Mechanical engineer.
- Regulatory specialist.
- Chemist.
- Cost engineer.
- Geologist/geotechnical engineer/hydrogeologist.
- Civil/structural engineer.
- Soil scientist/soil physicist.
- Electrical engineer.

The level of involvement will vary among the disciplines; some disciplines will have a major role and will require many hours to provide input whereas other disciplines will consult on specific issues. Frequent interchange of information among disciplines is to be strongly encouraged. It is especially important that those involved with subsurface and aboveground components work together both during design and subsequent to start-up.

a. Subsurface strategy. A design strategy for SVE and BV systems starts with the recognition that the materials which can be removed from the subsurface with these systems are situated predominantly in the unsaturated zone and in the vicinity of the water table. The release mechanisms for moving these materials, and the rates at which they are released into the soil air and water, drive the design basis. Groundwater is not a medium that would effectively be remediated by SVE/BV alone.

(1) One of the first decisions to be made is whether to apply SVE, BV, or a combination of SVE/BV at the site. This decision will depend on the biodegradability, volatility, and concentrations of the contaminants of concern, as well as other considerations such as sensitive receptors, as discussed in paragraph 3-3.

(2) The primary design parameter is the air permeability of the soil, in both the vertical and horizontal directions, which is used in determining the "zone of effective air exchange" for each well at a given applied vacuum and airflow rate. In turn, the vacuum and flow rate can be adjusted to adequately ventilate the area of contamination and/or provide sufficient oxygen to stimulate microbial activity. The zone of effective air exchange is the volume of soil in which the air throughput is adequate to either volatilize contaminant in a reasonable target time or to provide adequate oxygen to support biodegradation of the contaminant. Conservative estimates, historical experience, and bench- and/or pilot-study results can assist the design team in estimating the zone of effective air exchange and determining the exact placement and layout of wells for the full-scale remediation system. There is often an economic tradeoff between more wells operating at lower flow rates and fewer wells operating at higher vacuums and flow rates possibly using a larger blower. Figure 5-1 illustrates the steps that are recommended to properly design a SVE or BV system.



** For some sites. the pilot system will ultimately function as the full system.*

Figure 5-1. Decision tree for SVE/BV system design

(3) The design strategy for SVE systems is to promote the release of volatile compounds from the soil, NAPL, and water film covering the unsaturated soil so that they can be carried advectively under the influence of an applied vacuum to the surface for collection and treatment. For BV systems, the air movement provides a source of oxygen to diffuse into the water film, which promotes aerobic biodegradation of the contaminants dissolved in the water phase. In the subsurface, sufficient air movement is required to match the liberation rate from the soil and the microbial needs for oxygen.

(4) In an ideal SVE design, the rate of transfer of volatile contaminants from the soil and water into the soil air would match the rate of air movement to the surface, so contaminants in the air stream would remain as concentrated as possible. In practice, maximum contaminant concentrations occur shortly after start-up of the system, then decline from this concentration with time (unless there is an ongoing release). It is usually easy to provide a vacuum extraction system that will remove the existing contaminant vapors very quickly; but over time, due to diffusion or other constraints, the rate at which volatiles are removed from other "compartments" in the subsurface becomes increasingly independent of advection and increasingly dependent on diffusion, desorption, and other transport processes (paragraph 2-3*a*).

(5) The expected rate of transfer of volatile contaminants from the soil and water into the soil air needs to be considered prior to initiating the design of the subsurface venting system. Figure 5-2 presents a decision tree that outlines steps involved in carrying out these considerations. It should be noted that many of these steps may already have been considered during technology screening, but they need to be looked at again at the beginning of design so that new information (e.g., from laboratory- and/or pilot-scale testing) can be incorporated into the design process. Note that the process begins by reconsidering remedial goals relative to initial contaminant concentrations and the time available for cleanup. Next, the approximate number of pore volume exchanges required to achieve remedial goals within the available time frame, in the absence of mass transfer limitations, need to be selected. (The concepts of pore volume exchange rate and its reciprocal travel time, were introduced in paragraphs 4-5*f* (20) to (21). The required number of pore volume exchanges, divided by the available cleanup time, equals the limiting pore volume exchange rate.) There is a lack of agreement as to the total number of pore volume exchanges required for SVE. Some experts recommend as few as 200 to 400; others 2,000 to 5,000. Experience with similar sites and contaminants, column tests, or prolonged pilot tests have been suggested as predictive tools to estimate the required number of pore volume exchanges for a given site. Unless target cleanup goals are low or initial concentrations are very high, 1,000 to 1,500 pore volumes would be a good estimate of the required air exchanges. If the air exchange rates are too high, the removal of mass will be limited by diffusion kinetics. For BV, recommended pore volume exchange rates to meet microbial oxygen demand range from 1/4 to 1/2 d^{-1}. In other words, it is desirable to achieve pore-gas velocities in the treatment zone such that the maximum travel time is between 2 and 4 days from the edge of the treatment zone (where air contains high percentages of oxygen) to the extraction or injection wells. As discussed in section 5-3a(2), average pore-gas velocity is an alternate design criterion for developing an SVE/BV design. Current SVE research indicates that it is desirable to achieve pore-gas velocities throughout the treatment zone in excess of 0.001 cm/sec, or ~ 3 ft/day (DiGiulio and Ravi 1999). If performance specifications are to be used, the vacuums required at specific distances from the vent wells must be consistent with pressure gradients that yield adequate travel times or velocities. In summary, with either SVE or BV, potential rate limitations need to be reconsidered at this time, either quantitatively or qualitatively (Figure 5-2). Methods of doing so are described in the following four paragraphs.

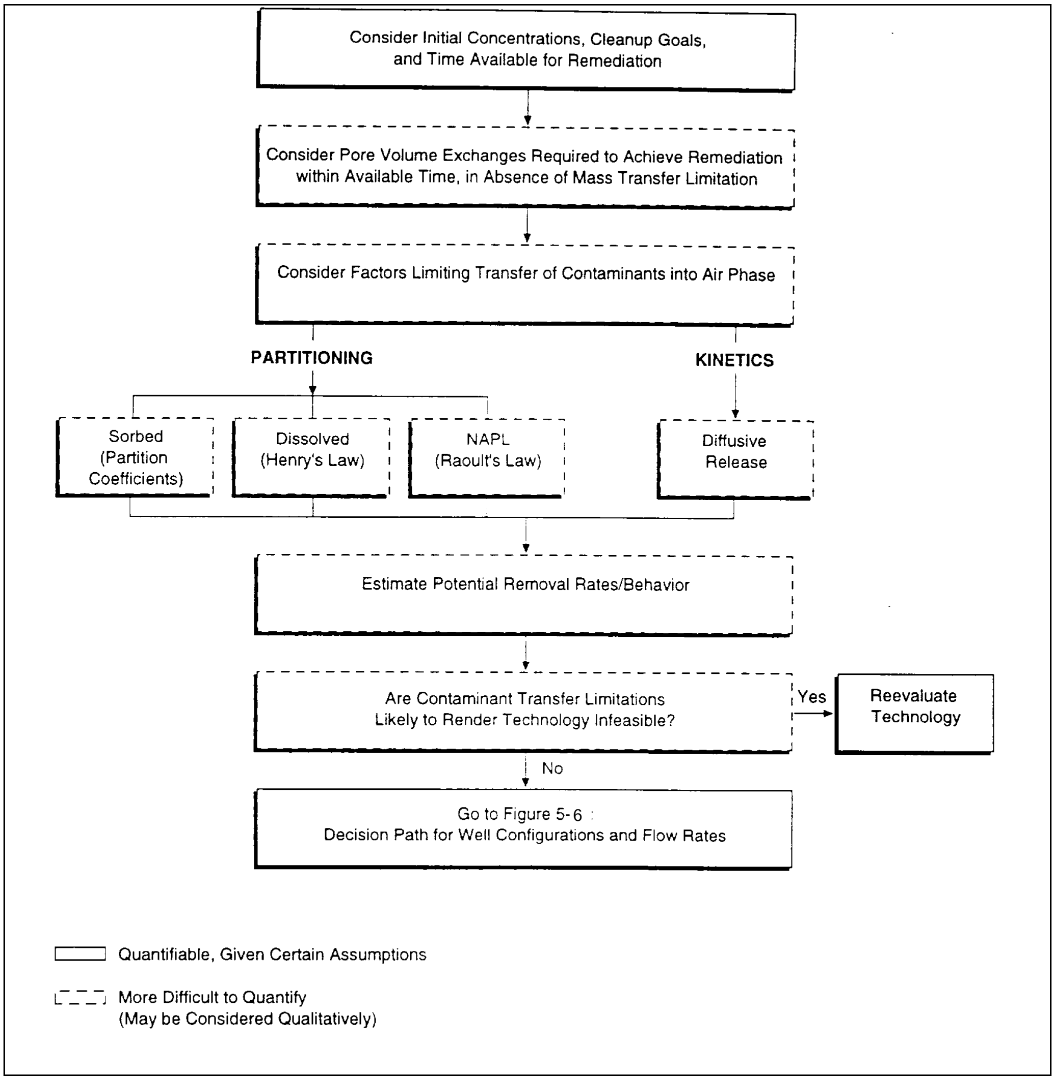


Figure 5-2. Considerations prior to well layout/airflow design.

(6) The zone of effective air exchange should correspond to the volume of soil that can be remediated within an acceptable time frame. To a certain extent, this zone can be expanded by increasing the flow rate from an individual vent. However, if the duration of remediation is too long, additional, more closely spaced wells should be operated with smaller zones of effective air exchange by decreasing the flow rate from individual vents. As the system is operated, less airflow may be required as portions of the site achieve goals and the number of operating vents may decrease. The blower selection should provide flexibility to account for these considerations. Use of a variable speed motor drive (i.e., VFD) for the vacuum blower is an excellent method of achieving the necessary flexibility.

(7) Consider injection of air during the development of a SVE strategy. Most importantly, air injection increases air throughput. Air injection can enhance air throughput without the need for higher vacuums which may cause undesirable water table upwelling. It can also limit infiltration of vapors from other sites. Air injection can be passive, dependent on atmospheric air entry into an open well based on the vacuum felt by the well screen, or active, where a blower is used to force air into the subsurface. Though rarely used, air injection can be an effective tool in SVE design.

(8) For bioventing, excessive aeration of the subsurface will not only satisfy the oxygen demand, promoting biodegradation, but more VOCs will be removed to the surface than with a slower airflow. BV systems should degrade as much contamination in the subsurface as possible to minimize the release of VOCs to the atmosphere or the need to destroy these compounds at the surface. The required volume of air per time may change as cleanup progresses due to partial remediation and reduced oxygen demand as the more easily degraded compounds are lost. Thus with BV, as with SVE, a vacuum pump or blower specification needs to consider operating requirements which may vary throughout the life of the project.

(9) Partitioning relations can be used to estimate contaminant removal rates as a function of time. Raoult's law, Henry's law, and soil vapor partitioning relations can be used to evaluate partitioning from NAPL, water, and soil, respectively. Changes in contaminant composition, and declining contaminant concentrations, must be considered when estimating future contaminant removal rates. Johnson and others (1990b) provide an evaluation of the change in gasoline composition with continued partitioning via Raoult's law. The assumption of equilibrium is often violated due to diffusion kinetics. Johnson and others (1990a) account for this limitation through the use of an "efficiency factor." The rates of diffusion can be computed based on assumed concentration gradients. If the computed diffusion rates appears to be too slow to remove mass from thick low-permeability strata, measures such as pneumatic fracturing or in-situ thermal treatment methods may be appropriate. Just such an approach has been proposed for a Marine Corps Air Station site in California (G. Kistner, EPA Region 9, personal communication 1999).

(10)Contaminant retardation should also be considered when estimating contaminant removal rates. As air travels toward an extraction vent, contaminants will sorb and desorb, and volatilize and dissolve, in response to changing soil conditions and contaminant concentrations. These processes commonly result in contaminant removal rates being far lower than would be the case were there no limitations to the release and movement of the contaminants with the advective airflow. The term “retardation” has been used to describe delayed contaminant removal resulting from sorption/desorption processes. However, the same concept applies to partitioning from dissolved and NAPL phases.

(11)Removal rates can be calculated using coupled airflow and contaminant partitioning models, or they can be estimated based on pilot tests and column studies. Although airflow models usually provide reasonable estimates of vapor flow rates and travel times, contaminant partitioning is more difficult to simulate. This results from the numerous interrelated processes involved, and the physical and chemical properties of heterogeneous soil. With caution, experienced modelers may obtain estimated contaminant removal rates via modeling. Alternatively, pilot studies or column tests can be used. The pilot tests can provide additional data against which models can be calibrated. The total time for remediation can be calculated by integrating the (often highly non-linear) estimated and extrapolated contaminant removal rate over time and comparing to estimates of the mass present.

(12) Observed mass removal rates can be calculated from vapor concentrations and flow rates using the equation presented in Table 7-4.

(13) In cases where a combined SVE/BV approach will be applied, the implications of the changeover from SVE to BV should be considered. Design considerations include:

- The likelihood that reduced airflow rates will be needed during BV.
- A dramatically changed monitoring program, including measurement of soil gas and offgas oxygen and carbon dioxide concentrations, pH, moisture, nutrient concentrations, and temperature.
- The possible need for additional wells due to the fact that with lower airflow rates, the zone of effective air exchange will be smaller. To some extent, this may be compensated for since BV often requires lower pore volume exchange rates and lower pore-gas velocities than SVE. Consequently, the definition of an acceptable vent spacing may change over the life of a project.

5-3. Well Locations

The number and locations of extraction and/or injection wells required to move air in the desired flow regime is highly site-specific and depends on many factors such as extent and depth of the contamination, physical and chemical properties of the contaminants, soil characteristics, and most important, air permeability.

a. Well layout. The primary goal of an SVE or BV system is to cause air transfer within the contaminated zone. For SVE systems, the goal is to provide air throughput at a rate that allows efficient transfer of contaminants but is still fast enough to remediate the soil within a desired time frame. For BV systems, the goal is to provide adequate air to prevent oxygen deficiency from being a limiting factor in bioremediation. The well layout must allow adequate air transfer within the target zone.

(1) Inadequacy of Radius of Influence (ROI) as Design Basis. In the past, designers have often used a "radius of influence" approach to choosing well spacing. The radius of influence (paragraph 4-5*f*), more accurately termed "radius of vacuum influence", has typically been defined based on some small but measurable vacuum (or pressure) level due to some extraction (or injection) rate. It is assumed that since vacuum is detectable, then air is moving and the soil is being treated. Well spacing would then be chosen on some factor, say 1.5 times the estimated radius of pressure influence at the projected flow rate. Unfortunately, this fails to consider the actual air throughput at points intermediate between vents. There may be minimal flow in these areas.

(a) Problems associated with ROI-based venting designs have been discussed in refereed literature (Johnson and Ettinger 1994; Nyer et al. 1994), yet, ROI testing continues to be used for venting design at many sites. Practitioners who use ROI testing to design soil venting systems assume that observation of subsurface vacuum ensures sufficient airflow in contaminated soils for timely remediation via organic compound volatilization and/or biodegradation. As Johnson and Ettinger (1994) point out, however, measurement of vacuum says very little about pore-gas velocities that prevail within the subsurface. Pore-gas velocity is proportional to the product of the pressure gradient (i.e., pressure difference over a given distance within the soil) and the air permeability within that soil. **Since air permeability, k_a, can often vary 100 to 10,000-fold from one soil type to another, it is the k_a value within the soil, rather than the pressure gradient, that usually governs the pore-gas velocity.** For example, a soil consisting of two layers having contrasting air permeabilities that are both subjected to the same applied vacuum along a lateral boundary will, upon attainment of a steady state, exhibit exactly the same pressure gradient in both the high and low permeability layers. Meanwhile, however, the pore-gas velocity can be orders of magnitude greater within the high permeability layer than within the adjacent low permeability layer (Figure 5-3).

(b) Consequently, basing a venting design on measurement of vacuums alone, at best, only ensures capture and containment of contaminant vapors. (In other words, observation of a measurable vacuum does indicate that there is a pressure gradient in the direction of the vacuum well, and therefore that there may be some movement in that direction, not how fast air will flow toward that well.) Even containment comes into question when the magnitude of applied vacuum in soil is so small as to be comparable to pressure differentials caused by natural variation in barometric pressure and/or fluctuation of the water table. Diurnal barometric pressure changes in soil can be on the order of a few mbar (Massmann and Farrier, 1992), whereas 0.1 inch water vacuum (the value often adopted by ROI practitioners as indicative of significant vacuum) is equivalent to only 0.25 mbar. Thus natural pressure gradients can overwhelm the smaller pressure gradients exerted at a distance from venting wells.

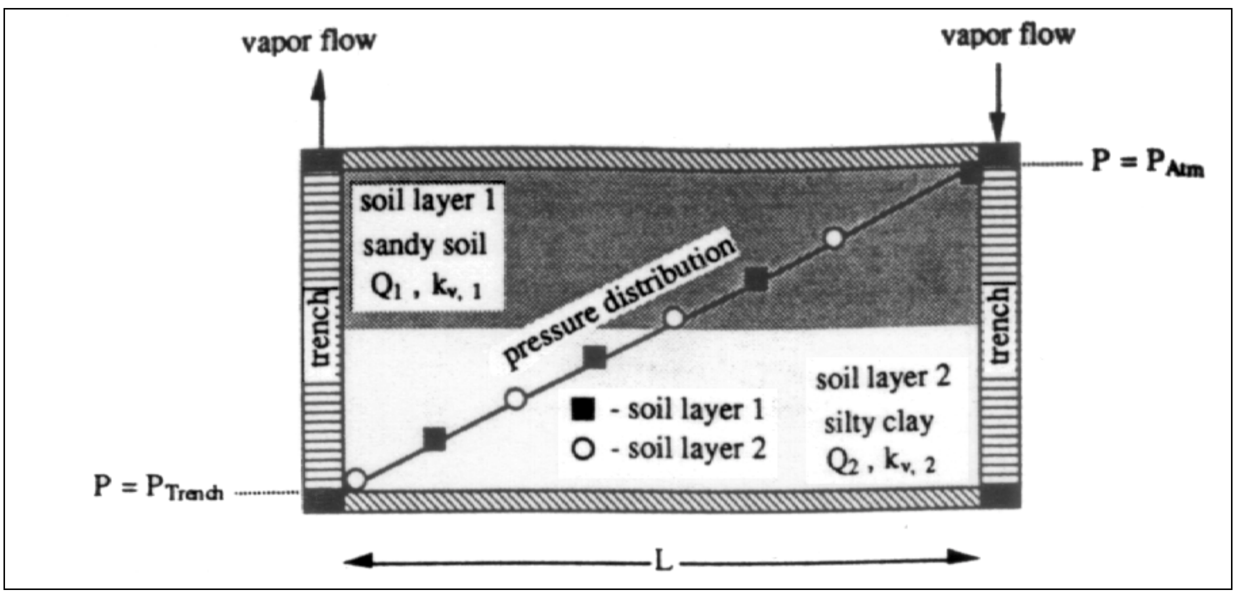


Figure 5-3. Effect of Contrasting Air Permeabilities on Pore-Gas Velocity. Figure depicts steady-state pressure distribution for 1-D flow between parallel trenches. Trenches intersect two soil strata with contrasting permeabilities (one sand and the other silty clay). Although the pressure distributions are the same in the two strata, most of the airflow will occur through the sand (Johnson and Ettinger, 1994).

(2) Pore-Gas Velocity or Travel Times as a Preferred Design Basis. A more relevant approach to well layout is to try to achieve a pore velocity that exceeds some minimum rate, everywhere within the contaminated zone. This translates to a rate of air exchange (pore volume per time) that will lead to adequate cleanup in an allotted time. Analyses of air velocities and travel times to the extraction wells at various flow rates are thus required to verify adequate spacing (Shan, Falta, and Javandel 1992; Falta, Pruess, and Chestnut 1993). Required travel times can be estimated by dividing the time frame for remediation by the number of pore volumes required to remove a significant percentage of the contaminants. The pore volume exchanges must consider the flow paths along streamlines. In most cases where the site surface is not carefully sealed, the assumption that removal of air occurs via purely two-dimensional (horizontal) radial flow is inappropriate. Streamlines bound "streamtubes" or funnel-shaped volumes (narrowing toward the extraction vent) that conduct a given amount of air from a source, such as the atmosphere or an injection vent, to the extraction vent. The travel time through a streamtube is determined by dividing the air-filled pore volume in the tube by the flow rate of air through the tube. Streamtubes that have shorter paths from the surface or clean soil to the extraction vent will have shorter travel times than tubes that originate farther from the vent. The travel times for the tubes passing through the contaminated zone must be less than some value and the velocities at all points in the tube (within the contaminated volume or target cleanup area) must be above some threshold to achieve adequate air throughput. The product of the pressure gradient across that soil and the air permeability within it governs the pore-gas velocity within a given volume of the soil. Therefore, estimation of how pore-gas velocities will vary within the subsurface requires estimation, in turn, of both pressure gradient and air permeability within the zone in question. Computer models can be used for this analysis of velocities and travel times. Additional tools based on analytical equations describing air flow in porous media are provided below.

(a) Once a pore-gas velocity field is estimated, however, how does one know what minimum pore-gas velocity to specify as the minimum that must be attained within the contaminated domain in order for venting to be effective? Pore-gas velocities must be low enough to allow adequate time for diffusion from regions not receiving direct airflow, but high enough to avoid excessive build-up of vapors and hence excessive remediation time. Ideally, site-specific laboratory column and field studies would be conducted to determine this minimum value. Acceptable laboratory and field-scale methodologies for this determination, however, are currently unavailable. In the absence of site-specific information, results of published research can be used to estimate a minimum design pore-gas velocity or specific discharge value.

(b) A number of laboratory-scale investigations indicate that pore-gas velocities at which rate-limited vapor transport is observed are much higher for NAPL contaminated soils than non-NAPL contaminated soils. Thus, when selecting a minimum pore-gas velocity for venting design, one should distinguish whether or not NAPL is present in soils. However, even if soils are contaminated by NAPL, it may be unwise to base selection of a design pore-gas velocity totally on mass transport in NAPL contaminated soils, since time spent on venting application after eventual removal or evaporation of NAPL can be substantial.

(c) Virtually all research on selection of pore-gas velocities for venting remediation has been conducted in controlled sand tanks and laboratory columns where field-scale heterogeneity is not a factor. Thus, optimal pore-gas velocities in the field are likely to be very site-specific and somewhat smaller than indicated by controlled sand tank and laboratory column studies.

(d) The characteristic length of contamination used in equations developed to estimate design pore-gas velocities is not constant but decreases in time due to NAPL and sorbed mass removal, thereby reducing calculated optimal pore-gas velocities.

(e) The cost of well installation versus venting operation (e.g., electricity, vapor treatment) must be considered since achievement of a minimum target pore-gas velocity in contaminated soils is largely determined by balancing applied flow and spacing of venting wells. An increase in the number of venting wells results in a decrease in applied flow to achieve similar pore-gas velocities in soils. Thus, operating costs associated with blower operation and vapor treatment can be reduced by increasing construction costs associated with well drilling.

(f) In consideration of these factors, it is apparent that selection of a minimum pore-gas velocity is not a straightforward process but involves some degree of engineering judgement. Experimental sand tank and column studies suggest that pore-gas velocities in excess of 0.25 cm/s (Wilkins et al., 1995) must be present in NAPL contaminated soil for deviation from local equilibrium, while studies by Armstrong et al. (1994), Gierke et al. (1992), and Ng and Mei (1996) suggest an optimal pore-gas velocity near 0.01 cm/s for non-NAPL contaminated soils. Since the longest portion of venting operation may be associated with mass removal after evaporation of NAPL and specification of a design pore-gas velocity of 0.01 cm/s or greater will generally result in unacceptably close well spacing for a variety of site designs, **it is currently recommended that a minimum pore-gas velocity between 0.01 and 0.001 cm/s (DiGiulio and Ravi 1999), (or ~ 3 to 30 ft/day) be used for design purposes**. Cho and DiGiulio (1992) provide an example of pore-gas velocity calculations. Public domain computer codes developed by the USGS, AIR2D (Joss and Baehr, 1997) and AIR3D (Joss and Baehr, 1995) provide specific discharge calculations in axi-symmetric and three-dimensional cartesian coordinates, respectively.

(3) *Air Injection for Soil Vapor Extraction.* Air injection offers benefits in operation such as reduction of "dead zones", minimization of upwelling, increasing pressure gradients, and creating a barrier to air flow toward sensitive locations, as discussed in the following paragraphs.

(a) At sites requiring multiple wells, areas of little or no airflow are established near the intersections of the effects of the nearby wells. This can be overcome either through operation of nearby wells at varying flow rates to move the stagnation point over time or by the use of air injection wells (Figures 5-4, 5-5, and 5-6). Passive air injection wells allow air entry directly from the atmosphere into the subsurface and can significantly alter air flow, increasing flow in stagnation areas. However, since the air intake at a passive injection well is a function of the vacuum in the subsurface at the passive injection well screen and since the vacuums at the stagnation areas are often small, the actual air entry is often minor. Active air injection can be much more effective at increasing air throughput in these areas, possibly resulting in expedited remediation since these areas are often the last to clean up without air injection. Computer models can be used to project the effect of passive or active air injection wells.

(b) At sites where the contaminant mass to be removed is located near the water table, the exclusive use of vapor extraction results in maximum upwelling of the water table and capillary fringe due to the applied vacuum. This would likely reduce the effectiveness of treatment near the extraction well. The coupled use of air injection and air extraction reduces the applied vacuum "felt" by the water table for the same amount of air flow through the soils. Furthermore, the injected air can be focused in the vicinity of the water table, reducing the effort spent in moving air through relatively clean soil higher in the vadose zone. This increases effectiveness for the operation cost. Although paired extraction and injection requires additional blower(s) or blower capacity, the reduction, due to the smaller required vacuum, in the sizing of the blower(s) and the possible increase in well spacing will likely reduce overall capital costs and operational costs. In other cases where focused airflow in a specific horizon is required, the use of active air injection can also benefit the project. Computer modeling or the analytical tools described below can be used to determine the impact of air injection. The addition of clean air to the subsurface, if not properly considered, may also dilute vapor phase contaminant concentrations, thereby increasing offgas treatment costs.

(c) Passive inlet wells are typically used to limit the radius of influence of a particular well. An example would be the case where two adjacent properties have volatile contaminants in the subsurface. A passive inlet system installed along the property boundary would allow SVE/BV to proceed at one of the properties without inducing migration of contaminants from the other property, but the inlet wells would probably need to be quite closely spaced to create an effective boundary condition.

(d) As mentioned in Chapter 3, passive venting as the sole air addition and/or removal mechanism can be used if there is adequate lag in response between the subsurface and the atmosphere. Evaluation of the pressure lag, air removal (or injection for BV) rates, and air exchange in the surrounding subsurface is required for design of a passive system.

(e) Steam can be injected instead of air to enhance the removal of low volatility contaminants or to enhance diffusion, as discussed in more detail in Chapter 3.

b. Extraction well screen placement.

(1) The main objective in extraction well placement is to induce air to flow through the zone of contamination. Well screen placements range from screening the entire unsaturated zone to screening a short interval corresponding to the thickness of a highly contaminated zone. In general, extraction wells should only be screened within the zone that has been impacted.

(2) If groundwater has been impacted, the greatest concentrations of vapors will often be found immediately above the water table, especially when free floating product is encountered. In this case, the screened sections of the wells should be placed in proximity to the water table for optimal removal efficiency (but with some portion of the vent screen extending far enough from the water table to prevent upwelling from occluding the screen). Additionally, the placement of the well screen deeper in the soil column has been shown, both analytically and empirically, to maximize the air flow paths and, therefore, the zone of effective air exchange of a given extraction well (Shan, Falta, and Javandel 1992). It is strongly suggested that flow models such as AIR2D, AIR3D, or MODFLOW (with appropriate modifications) be used to optimize screen depths. These and other SVE/BV models are described in Appendix C.

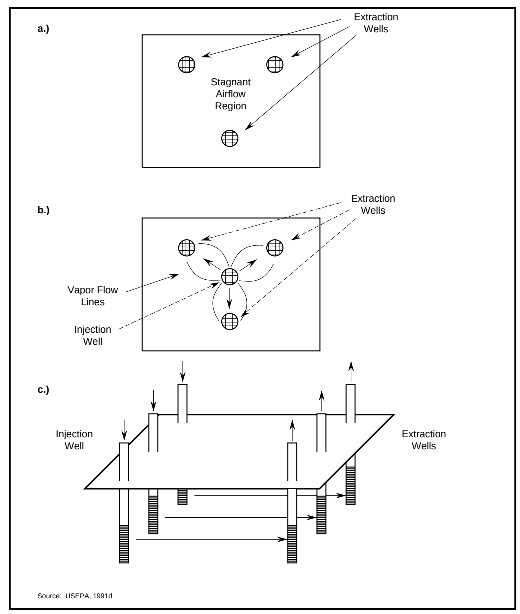


Figure 5-4. Example venting well configurations.

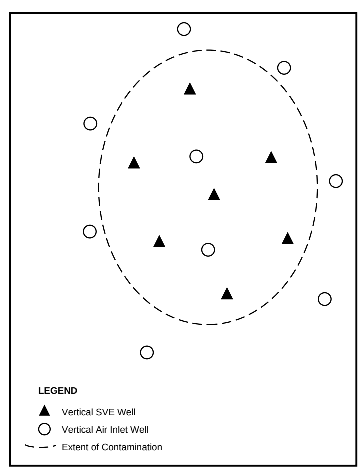


Figure 5-5. Vertical extraction/inlet well layout scheme (asymmetric layout reflects anisotropic conditions at site).

(3) In areas where the water table is shallow (i.e., less than 3 meters below ground surface), horizontal SVE/BV wells or trenches should generally be employed. Horizontal SVE/BV wells minimize the upwelling of groundwater and in such cases extract air from the unsaturated zone more efficiently.

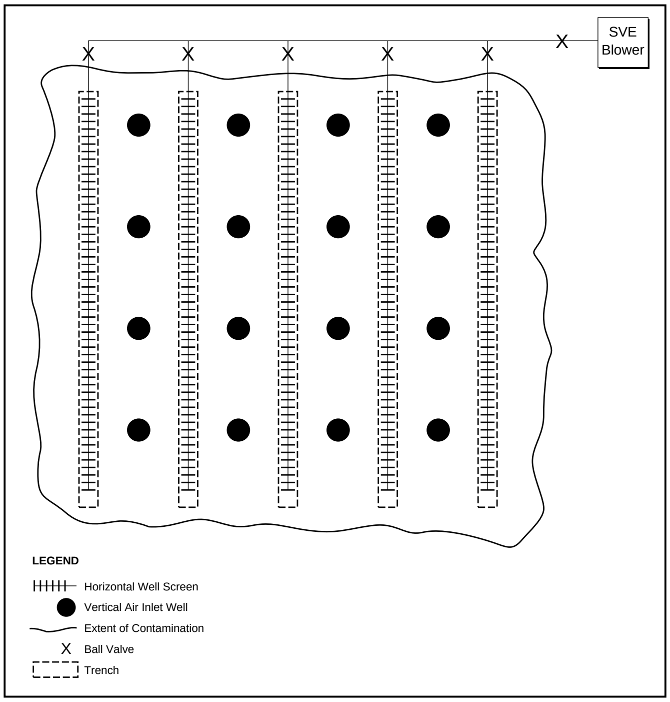


Figure 5-6. Plan view of typical horizontal extraction/vertical inlet well scheme.

c. Passive/active injection well placement

(1) Injection wells should be placed so that contamination is directed toward the extraction wells and not driven into uncontaminated areas or toward possible exposure points. Although screened intervals vary in length, they should allow for uniform airflow from the injection to the extraction wells. Injection wells are usually installed vertically outside the edge of the contaminated area. A well-designed soil venting system allows vents to act interchangeably as extraction, injection, and/or passive inlet wells. Passive/active injection wells are similar in construction to extraction wells (refer to paragraph 5-4), and the screened intervals are chosen to focus airflow into the appropriate zone to enhance contaminant recovery. Steam injection wells are typically constructed of steel.

d. Decision path for selecting well configurations and flow rates

(1) A decision path for selecting well configurations and flow rates is shown on Figure 5-7. The decision path focuses on single vs. multiwell systems comprised of up to four wells. The multiwell systems consist of a central extraction well surrounded by one, two, or three injection wells. SVE subsurface airflow velocity modeling or streamtube calculations are used to determine the required extraction rate and well configuration to achieve a desired air exchange rate. For sites with impermeable surface covers, the total injection rate is assumed to be equal to total extraction rate. This pumping strategy makes maximum use of the injection wells without causing offsite migration of contaminated vapors. For sites without impermeable surface covers, the extraction rate must exceed the total injection rate, since some of the extracted air represents breakthrough from the atmosphere.

(2) The multiwell systems evaluated represent typical well configurations for SVE and BV applications. These configurations represent somewhat idealized geometries that are unlikely to be reproduced exactly during field installation. However, the well configurations shown can be used as a guide for SVE/BV design. Well spacings and flow rates for other well and trench configurations can be determined using a similar approach.

(3) The primary considerations for selection of well configurations and flow rates are a) the geometry of the contaminated zone, b) the air permeability and horizontal to vertical permeability ratio, and c) the desired air exchange rate. Using these data, well configurations and flow rates can be systematically evaluated using the nested decision loops shown in Figure 5-7. Each well configuration in the outer "Well Configuration" loop is evaluated against offgas treatment limitations, blower horsepower, and water table upwelling limitations in the inner "Acceptance Criteria" loop. The following paragraphs explain the actions required at each step of the decision path.

(4) In conjunction with the flow rate that can be achieved by individual wells, the size of the contaminated zone exerts the predominant control on the number of wells that will be required. Similarly, the geometry of the contaminated zone controls the spatial configuration and optimum screened intervals of the wells.

(5) Either air permeability measurements or pilot test data are required to evaluate blower horsepower and water table upwelling, whereas anisotropy measurements (the ratio of horizontal to vertical permeability) are required to evaluate well configurations. Recommended methods for analysis of air permeability and anisotropy are presented in Appendix D.

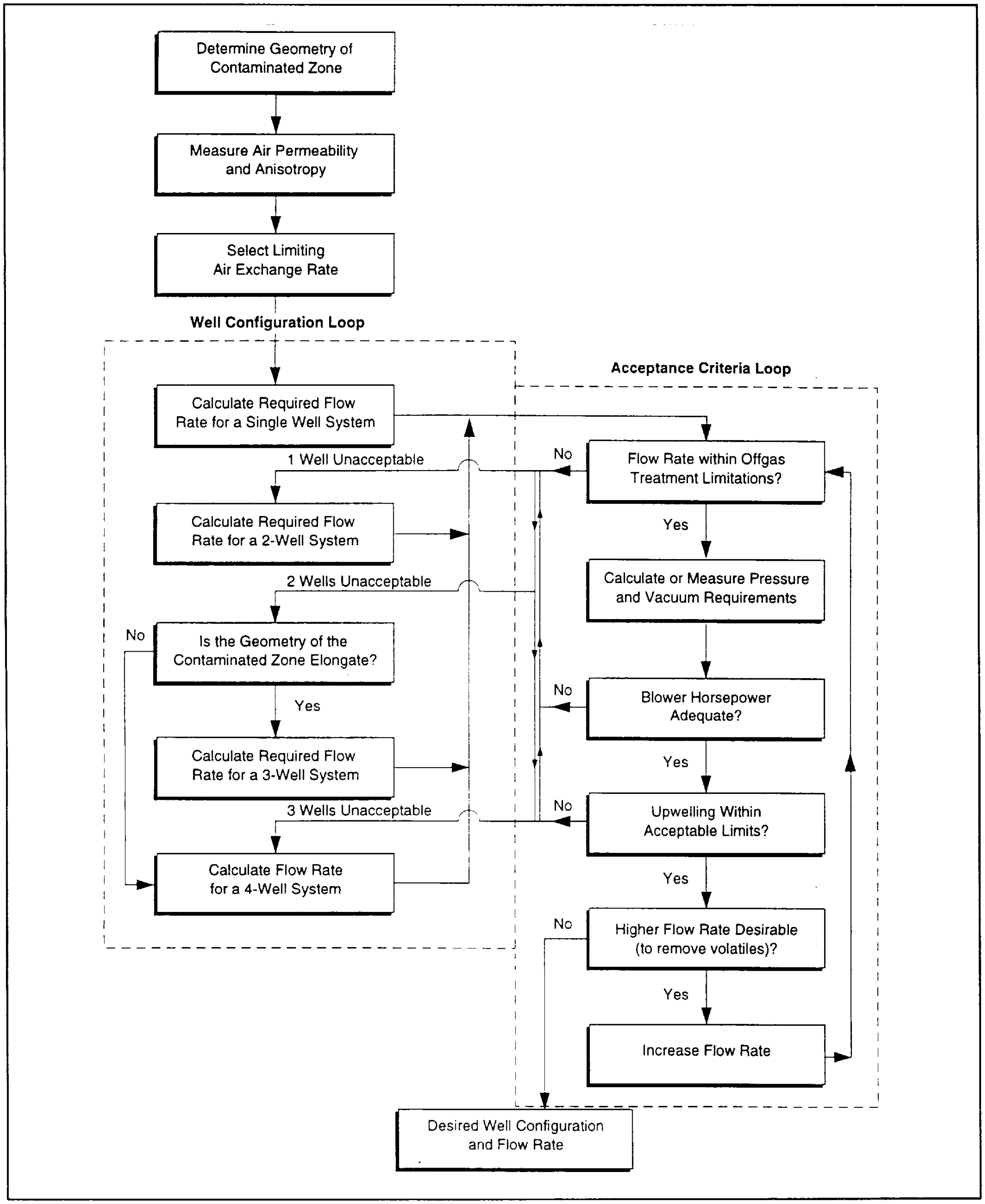


Figure 5-7. Decision path for well configurations and flow rates.

For this development, flow rate calculations are based on a minimum air exchange rate within the contaminated zone. This approach is probably more valid for BV applications, where air exchange rates are low enough that sorption and diffusion limitations are less important. If the minimum air exchange rate exceeds the rate of contaminant release from diffusion- or sorption-limited zones (as for some SVE applications), this approach is not valid. Pilot tests or column studies may be useful for identifying the minimum air exchange rate.

(6) Because single well systems generally involve the lowest installation cost, these systems form the first tier of the well configuration loop (Figure 5-7). For sites **with impermeable surface covers**, the required flow rate for a single well system can be calculated via:

$$Q_v^* = \frac{\pi r^2 b n_a}{t_{ex}} \tag{5-1}$$

where

Q_v^* = volumetric flow rate at atmospheric pressure [L^3/T]

r = radius of the treatment zone [L]

b = vadose zone thickness [L]

n_a = air-filled porosity of the soil [L^3/L^3]

t_{ex} = the time required for one pore volume exchange [T]

Equation 5-1 is based on the assumption of incompressible flow, which is valid for applied vacuums less than about 0.2 atmospheres, gauge. For vacuums exceeding this level, the extraction rate should be multiplied by a factor of safety proportional to the applied vacuum.

(7) For sites without impermeable surface covers, flow rate calculations require determination of the travel time from the limits of contamination to the extraction well. If the maximum extent of contamination occurs near the ground surface, dimensionless travel times provided by Shan, Falta, and Javendal (1992) can be used to determine the required flow rate. Using the definition of dimensionless travel time provided by them, the required flow rate for a single well system is:

$$Q_v^* = \frac{2 \pi b^2 \; n_a \, A \, (L - l \,) \, \tau}{t_{ex}} \tag{5-2}$$

where:

Q_v^* = volumetric flow rate at atmospheric pressure [L^3/T]

A = ratio of horizontal to vertical permeability

l = depth to the top of the well screen [L]

L = depth to the bottom of the well screen [L]

τ = dimensionless travel time from Shan et al. (1992)

This analysis is based on the travel time from the ground surface to the extraction well, as provided by Shan, Falta, and Javendal. The streamline originating near the lateral limits of the contamination is chosen as the critical (maximum travel time) path. The flow necessary to achieve an acceptable travel time along this path is chosen for design. If the maximum extent of contamination occurs near the water table, then dimensionless travel times obtained from Figure 5-8 may be used in Equation 5-2. It should be noted, however, that the dimensionless travel times shown in Figure 5-8 assume that there is no reduction in flow velocity due to increased water saturation near the water table.

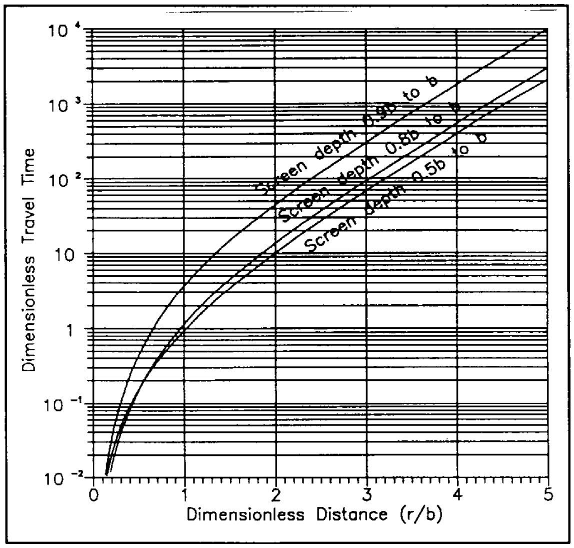


Figure 5-8. Dimensionless travel times at the water table for wells screened within the lower half, fifth, and tenth of the vadose zone (Brailey 1995, unpublished data).

(8) To evaluate the adequacy of a single well system, the flow rate obtained from Equation 5-1 or 5-2 should be compared against the acceptance criteria shown in Figure 5-7. Since the vacuum necessary to develop the design flow rate may exceed blower horsepower or water table upwelling limitations, vacuum requirements should be measured or calculated using the appropriate flow equations. Well inefficiencies and friction losses through piping and equipment must also be considered. Alternatively, pilot test data can be used to estimate vacuum requirements.

(9) The following paragraphs discuss the design strategy for multi-well system that include active air injection. In many cases, the use of air injection adds significant benefit to the remediation by increasing air throughput at lower vacuums. If, however, air extraction is the only alternative for a larger system, then either the extrapolation of the results of the single well analysis, with some "factor of safety" to account for stagnation zones, or numerical modeling should be applied to determine optimum well placement. Again, the goal is to achieve a minimum velocity or some maximum travel time along the longest air streamline.

(10) If the required flow rate for a single well system exceeds the acceptance criteria shown in Figure 5-7, the decision path aborts to evaluation of two-well systems (paired extraction and injection wells). For sites with impermeable surface covers, flow from an injection well to an extraction well is primarily horizontal, and can be represented in plan view as shown in Figure 5-9. Note that in the streamtube plots that follow, each of the streamtubes transmits an equal fraction of the total airflow represented within the drawing.

(11) The flow geometry shown in Figure 5-9 applies where the extraction rate equals the injection rate. As shown in Figure 5-9, about 50 percent of the flow occurs inside a circle containing both wells. Flow outside the circle is relatively slow (indicated by the width of the streamtubes), and has potential for offsite migration of contaminants. As a result, the wells should be placed at either end of the maximum horizontal extent of the treatment zone. In this manner, the streamtubes with the highest flow velocity lie directly between the two wells, and there is limited potential for offsite migration of contaminated vapors.

(12) Note that the two-well geometry is somewhat inefficient, because about 50 percent of the flow occurs outside the treatment zone. As a result, this geometry is appropriate where there is limited resistance to flow, and the system capacity is adequate for ventilation of soils both within and outside the treatment zone.

(13) The required flow rate for a two-well system can be obtained by setting the air exchange rate in the outermost streamtube equal to the design criterion. The outermost streamtube of the treatment zone corresponds to streamtube No. 6 in Figure 5-9. Noting that streamtube No. 6 carries 1/20 of the design flow rate, the travel time from the injection well to the extraction well is:

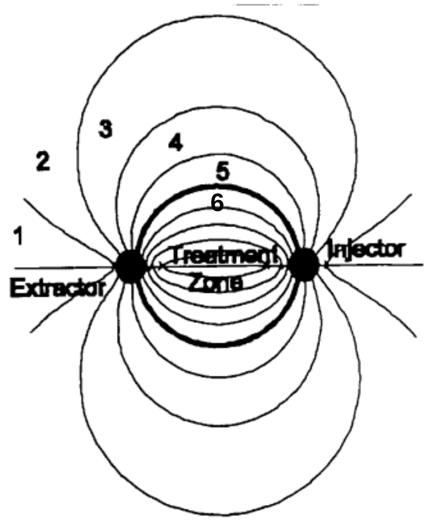
$$t = \frac{V_{\#6}}{\frac{1}{20} Q_v^*} = \frac{0.133 L^2 \; b n_a}{\frac{1}{20} Q_v^*} = \frac{2.66 L^2 \; b \, n_a}{Q_v^*} \tag{5-3}$$

where

` $V_{\#6}$ = volume of streamtube No. 6 [L^3]

Q_v^* = volumetric flow rate at atmospheric pressure [L^3/T]

L = distance between the two wells [L]



Dimensionless Streamtube Areas (x 10^2)

Tube	Area	Tube	Area
1	∞	6	13.3 L^2
2	603 L^2	7	9.21 L^2
3	115 L^2	8	7.12 L^2
4	42.8 L^2	9	6.65 L^2
5	21.8 L^2	10	4.74 L^2

L = well spacing

Brailey (1995), unpublished data

Figure 5-9. Plan view of streamtubes for a two-well system

To determine the required flow rate, use Equation 5-4 setting the time for one pore volume exchange (t_{ex}) equal to the design criterion:

$$Q = \frac{2.66 L^2 \; b \; n_a}{t_{ex}} \tag{5-4}$$

Equation 5-4 is based on the assumption of incompressible flow, which is valid for applied vacuums less than about 0.2 atmospheres, gauge. For vacuums exceeding this level, the extraction rate should be multiplied by a factor of safety proportional to the applied vacuum.

(14) For sites without impermeable surface covers, the three-dimensional flow geometry makes plan view representation difficult. Close to the water table, however, the flow geometry is similar to that shown in Figure 5-10. In cross section, the flow geometry for wells screened within the bottom third of the vadose zone, with a well spacing equal to $1.6bA^{1/2}$, is shown in Figure 5-10. This well spacing represents the maximum spacing that will not cause substantial breakthrough of atmospheric air between the extraction well and the injection well.

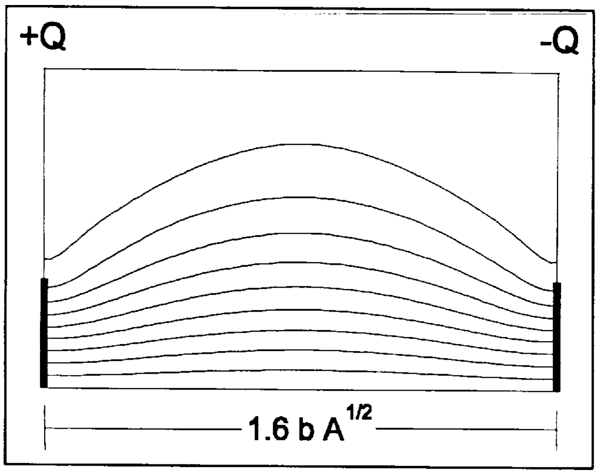


Figure 5-10. Profile of streamtubes for a two-well system.

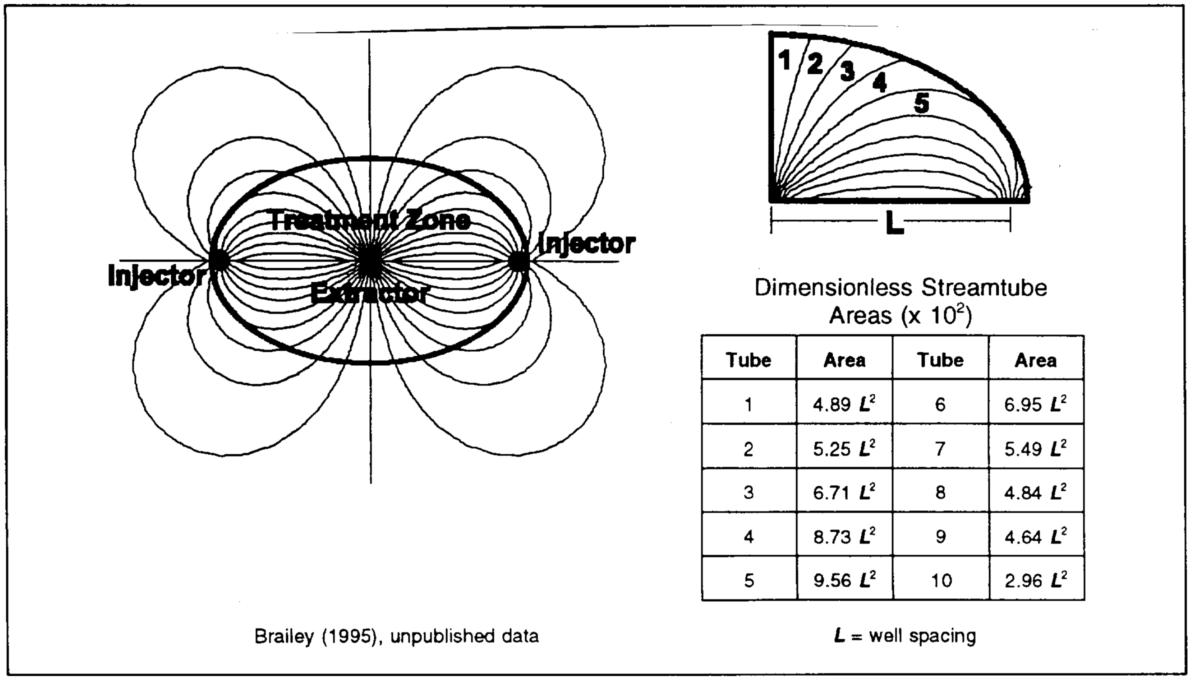
For wells screened within the bottom third of the vadose zone, the required flow rate can be determined by first verifying that $L \leq 1.6bA^{1/2}$. Then, Equation 5-4 can be used to calculate the required flow rate.

(15) The amount of atmospheric breakthrough can be controlled by changing the well spacing, screened interval, and flow rate. Although smaller well spacings will result in less atmospheric breakthrough, streamtube modeling is required to evaluate well spacings and screened intervals other than those shown in Figure 5-10.

(16) If an adequate air exchange rate cannot be accomplished with a two-well system, then three- or four-well configurations may be evaluated. If the contaminated zone is elongated in plan view, then a three-well system should be considered. If the contaminated zone is roughly symmetric in plan view, then a four-well configuration is more appropriate.

(17) As shown by Figure 5-11, three-well systems are best suited for elongated treatment zones. For sites with impermeable surface covers, flow from an injection well to an extraction well is primarily horizontal, and can be represented in plan view as shown in Figure 5-11.

(18) The flow geometry shown in Figure 5-11 applies where the total injection rate equals the total extraction rate. As a result, the flow rate into each injector is one-half of the flow rate from the central extractor. As shown in Figure 5-11, about 60 percent of the flow from injection to extraction wells falls within an ellipse, where the width-to-length ratio of the ellipse is about 0.65. Flow outside the ellipse is relatively slow, and has potential to cause offsite migration of contaminants. As a result, two wells should be placed at either end of the treatment zone, and a third well should be placed along the centerline midway between the outer wells. In this manner, the streamtubes with the highest flow velocity lie directly between the two wells, and there is limited potential for offsite migration of contaminated vapors.



Tube	Area	Tube	Area
1	4.89 L^2	6	6.95 L^2
2	5.25 L^2	7	5.49 L^2
3	6.71 L^2	8	4.84 L^2
4	8.73 L^2	9	4.64 L^2
5	9.56 L^2	10	2.96 L^2

Figure 5-11. Plan view of streamtubes for a three-well system.

(19) The required flow rate for a three-well system can be obtained by setting the air exchange rate in the outermost streamtube equal to the design criterion. The outermost streamtube of the treatment zone corresponds to streamtube No. 5 in Figure 5-11. Noting that streamtube No. 5 carries 1/40 of the design flow rate, the travel time from the injection wells to the extraction well is:

$$t = \frac{V_{\#5}}{\frac{1}{40} Q_v^*} = \frac{0.0956 L^2 \, b n_a}{\frac{1}{40} Q_v^*} = \frac{3.82 L^2 \, b n_a}{Q_v^*} \qquad (5\text{-}5)$$

where

$V_{\#5}$ = volume of streamtube No. 5 [L^3]

To determine the required flow rate, use Equation 5-6 setting the time for one pore volume exchange (t_{ex}) equal to the design criterion:

$$Q = \frac{3.82 L^2 \, b n_a}{t_{ex}} \qquad (5\text{-}6)$$

Equation 5-6 is based on the assumption of incompressible flow, which is valid for applied vacuums less than about 0.2 atmospheres, gauge. For vacuums exceeding this level, the extraction rate should be multiplied by a factor of safety proportional to the applied vacuum.

(20) For sites without impermeable surface covers, the three-dimensional flow geometry makes plan view representation difficult. Close to the water table, however, the flow geometry is similar to that shown in Figure 5-12. In cross section, the flow geometry for wells screened within the bottom third of the vadose

zone, with a well spacing of $1.6bA^{1/2}$, is shown in Figure 5-12. This well spacing results in only minor breakthrough of atmospheric air along the longitudinal axis of the treatment zone (A-A'), but there is substantial breakthrough in the transverse direction (B-B'). For wells screened within the bottom third of the vadose zone with a well spacing of $1.6bA^{1/2}$, the extraction rate calculated using Equation 5-6 should be increased by about 50 percent to account for the breakthrough shown on B-B'. The injection rate, however, should remain the same.

(21) The amount of atmospheric breakthrough can be controlled by changing the well spacing, screened interval, and flow rate. Although smaller well spacings will result in less atmospheric breakthrough, streamtube modeling is required to evaluate well spacings other than those shown in Figure 5-12.

(22) As shown in Figure 5-13, four-well systems are best suited for treatment zones that are symmetric in plan view. For sites with an impermeable surface cover, flow from injection wells to extraction wells is primarily horizontal, and can be represented in plan view as shown in Figure 5-13.

(23) The flow geometry shown in Figure 5-13 applies where the total injection rate equals the total extraction rate. As a result, the flow rate into each injector is one-third of the flow rate from the central extractor. Placement of injection wells at the limit of the treatment zone avoids relatively low flow rates near the perimeter of the flow field (indicated by the width of the streamtubes). This well placement also limits the potential for offsite migration of contaminated vapors.

(24) The required flow rate for a four-well system can be obtained by setting the air exchange rate in the outermost streamtube equal to the design criterion. The outermost streamtube of the treatment zone corresponds to streamtube No. 1 in Figure 5-13. Noting that streamtube No. 1 carries 1/60 of the design flow rate, the travel time from the injection wells to the extraction well is:

$$t = \frac{V_{\#1}}{\frac{1}{60} Q_v^*} = \frac{0.0754\, L^2\, b\, n_a}{\frac{1}{60} Q_v^*} = \frac{4.52\, L^2\, b n_a}{Q_v^*} \tag{5-7}$$

where

$V_{\#1}$ = volume of streamtube No. 1 [L^3]

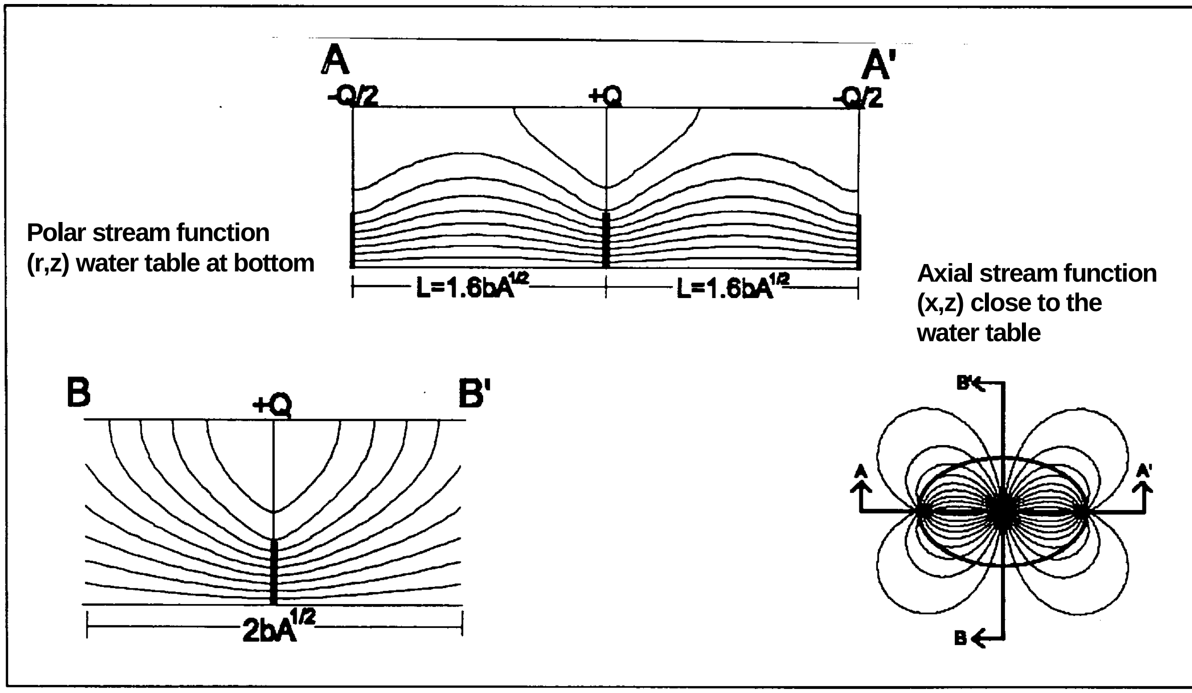
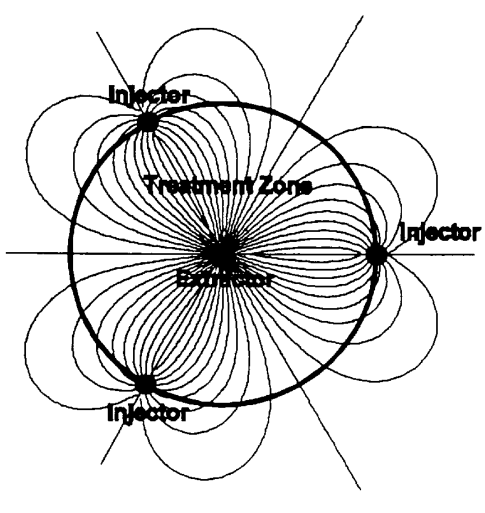
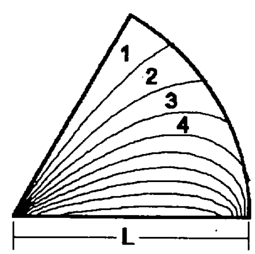


Figure 5-12. Streamtube profiles for a three-well system.





Dimensionless Streamtube
Areas (x 10^2)

Tube	Area	Tube	Area
1	7.54 L^2	6	4.80 L^2
2	7.53 L^2	7	4.04 L^2
3	7.15 L^2	8	3.64 L^2
4	6.80 L^2	9	3.63 L^2
5	6.00 L^2	10	2.36 L^2

Brailey (1994), unpublished data

L = well spacing

Figure 5-13. Plan view of streamtubes for a four-well system.

To determine the required flow rate, use Equation 5-8 setting the time for one pore volume exchange (t_{ex}) equal to the design criterion:

$$Q = \frac{4.52\, L^2\, b\, n_a}{t_{ex}} \tag{5-8}$$

Equation 5-8 is based on the assumption of incompressible flow, which is valid for applied vacuums less than about 0.2 atmospheres, gauge. For vacuums exceeding this level, the extraction rate should be multiplied by a factor of safety proportional to the applied vacuum.

(25) For sites without impermeable surface covers, the three-dimensional flow geometry makes plan view representation difficult. Close to the water table, however, the flow geometry is similar to that shown in Figure 5-14. In cross section, the flow geometry for wells screened within the bottom third of the vadose zone, with well spacings of $bA^{½}$ and $1.6bA^{½}$, are shown in Figure 5-14. These well spacings result in minor breakthrough of atmospheric air between injectors and extractors, but there is significant breakthrough between individual injectors. For wells screened within the bottom third of the vadose zone with a well spacing of $1.6bA^{½}$, the extraction rate calculated using Equation 5-8 should be increased by about 50 percent to account for breakthrough between individual extractors. For wells screened within the bottom third of the vadose zone with a well spacing of $bA^{½}$, the extraction rate should be increased by about 30 percent. The injection rate, however, should remain the same.

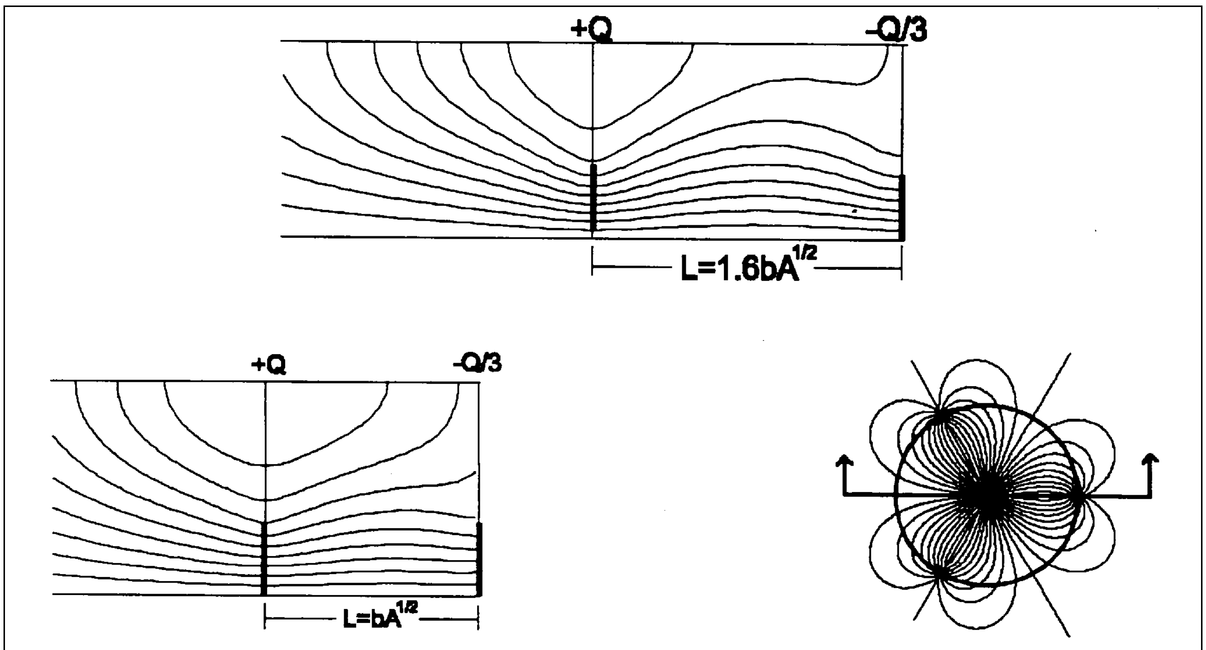


Figure 5-14. Streamtube profiles for a four-well system.

(26) The amount of atmospheric breakthrough can be controlled by changing the well spacing, screened interval, and flow rate. Although smaller well spacings will result in less atmospheric breakthrough, streamtube modeling is required to evaluate well spacings other than those shown in Figure 5-14.

e. Monitoring point locations and features.

(1) In order to determine the effectiveness of an SVE/BV remediation system, monitoring probes are installed adjacent to extraction wells. The monitoring probes can be used to determine the vacuum, soil gas concentrations, or temperature at any one point.

(2) To determine the vacuum at a monitoring probe, the probe is sealed with a threaded removable cap or septum to maintain a vacuum within the probe. A vacuum gauge or manometer may be tightly threaded through the top of the probe to provide continuous readings, or a pressure transducer may be employed to provide more sensitive readings of applied vacuum.

(3) Soil gas contaminant concentrations may be measured within the probe by connecting a small vacuum pump to the probe through a valve, and pumping the soil gas to a field instrument equipped with a flame ionization detector (FID) or a photoionization detector (PID). Alternatively, the sample of the soil gas can be captured in a Summa canister, gas-tight syringe, or on a sorbent, and analyzed on an on-site or off-site gas chromatograph.

(4) Typically, monitoring probes are constructed with minimal screened intervals so as to characterize parameters at distinct depths. It is strongly recommended that data be collected in three dimensions to account for heterogeneity and anisotropy of various parameters and conditions. The probes should be installed in clusters with multiple intervals screened to evaluate the variation in parameters with depth. In many cases, driven or pushed probes may be used and these may be very cost effective provided an adequate seal can be demonstrated between the screened interval and the surface. For a single extraction well, the installation of at least two monitoring point clusters at locations that characterize the site heterogeneity is recommended. Within each cluster, at least two different depths should be monitored individually, and more than one cluster can be situated along a given radial. For larger sites with many extraction points, the ratio of monitoring point clusters to extraction points can be reduced to between 1 and 2, as careful location of the monitoring points can supply data for more than one extraction point. As the size of the site and the number of extraction wells increases, it is usually not necessary to provide two monitoring points for each extraction well, although a ratio of at least 1 is recommended. Monitoring probes are most appropriate in areas that are least likely to get adequate air throughput, such as stagnation zones between extraction wells. Vacuum measurements and soil gas samples taken in those areas are very important in evaluating the system performance. More intensive monitoring can be conducted at locations with high concentrations of contaminants and that represent typical hydrogeologic conditions at the site.

(5) If the soil is heated to induce faster contaminant removal, temperature probes may be used to measure the thermal gradients at known distances from the heating source. In installations of temperature probes at multiple depths, the thermometer devices should generally be separated from each other in the well bore by at least 3 meters using grout plugs at least 1 meter thick. Temperature measurements are particularly important for BV applications or SVE applications that use passive/active air injection to induce biodegradation. Since biodegradation rates and vapor pressure are both strongly sensitive to

temperature, it is important to monitor these data, especially in locations where large seasonal fluctuations in temperature occur.

f. Integration with groundwater controls/free product recovery.

(1) In general, SVE or BV systems are not economical for the removal of significant amounts of free product. SVE has, however, been used successfully to remediate thin (less than 15 cm) lenses of volatile LNAPL, such as gasoline. Many SVE systems are operated in conjunction with a groundwater and/or free product recovery system (see paragraph 3-2e, and EM 1110-1-4010). The design team must be aware of the need as well as the potential for effective integration of SVE/BV with liquid phase remedial technologies. Integrated approaches to remediation of soil and groundwater are preferable over those that address one medium and neglect contamination in another interrelated medium.

(2) A primary design consideration is that the controls for the vacuum/air movement system should be compatible in operating logic with the pumping controls for the groundwater pumping system. If one system has a set of automatic shutoffs, the other systems should be similarly equipped. If a telemetric data collection system is used, it should be capable of recording data from both systems.

(3) As an example, bioslurping systems incorporating multiple extraction points are controlled by logic systems that shuttle the applied vacuum from one extraction point to another when the well ceases to collect product and begins to pull water, and when soil O_2 levels rise to above 15 percent, indicating the soil is adequately aerated.

g. Possible effects of nearby activities or contaminated sites. Adjacent contaminated sites may play an important role in determining the well locations of an SVE/BV system for the site to be treated. The wells should be placed in a configuration which will effectively treat the site without inducing onsite migration of contaminants from offsite sources. A set of passive wells at the property line may be used to create an effective barrier to onsite migration. This “picket fence” should consist of a series of wells screened throughout the depths of concern and typically not less than 1.5 meters apart. The well spacing will be dictated by air permeability. The wells may also be used as monitoring points to demonstrate the effectiveness of the passive wells in preventing cross-contamination from offsite.

5-4. Overall Pneumatic Considerations

a. It is important to consider overall system pneumatics prior to designing and selecting individual system components. A suggested approach is briefly summarized below and subsequently examined in more detail.

Step 1. Develop a relationship for vacuum level versus airflow in the subsurface.

Step 2. Calculate the friction loss for the system components and piping for a range of flow rate.

Step 3. Develop a “system” curve by adding the frictional losses calculated in steps 1 and 2.

Step 4. Research and select a blower and determine the blower curve.

Step 5. Predict the flow rate and vacuum level from the simultaneous (graphical) solution of the blower curve and the system curve.

Step 6. Balance the flows at each well, if necessary, and recalculate the vacuum levels.

(1) The first step has already been discussed. As mentioned in Chapter 4, site modeling or hand calculations based on pilot studies or bench-scale studies will allow the designer to predict the flow rate of air removed from the subsurface as a function of the vacuum (or pressure) level applied. Well efficiency for the vent must be considered in this step.

(2) The next step is to predict head loss through the system components for a range of flow rates. These calculations are fairly routine and not at all unique to SVE/BV systems. However, this manual will briefly discuss these calculations in order to lay the groundwork for further discussions that are more specific to the pneumatics of SVE/BV systems.

(a) The most common method of predicting friction losses in straight pipes is to use the Darcy-Weisbach equation:

$$h_f = (fL/d)(v^2/2g) \tag{5-9}$$

where

h_f = friction loss

f = friction factor

L =length of pipe

d =diameter of pipe

v = average pipe velocity

g = gravitational constant

The friction factor f is a dimensionless number that has been determined experimentally for turbulent flow and depends on the roughness of the interior of the pipe and the Reynolds number. Tables and charts have been developed to predict friction loss for a range of pipe sizes, liquids, and pipe materials (Spencer Turbine Co. 1987). Figure 5-15 is a friction loss chart that has been developed for inlet air at 294K and 101-KPa absolute pressure. Metric versions of these tables and charts are currently being produced in the industry and will be included as an addendum to this manual when available.

(b) There are two primary methods for estimating head losses through valves and fittings.

- Look up k values in tables (where $k = fL/d$ and, therefore, $h_f = kv^2/2g$) or
-

• Use tabulated values of equivalent length of straight pipe. For example, the resistance in a 150-mm (6-inch) standard elbow is equivalent to that of approximately 5 meters of 150-mm (6-inch) straight pipe.

(c) The friction losses from the subsurface, the straight pipe lengths, and the valves and fittings are added together to obtain the total friction loss at a given vacuum level. This calculation is repeated for several flow rates to establish a system curve. Note that these calculations are performed assuming that the valves are fully open.

(d) The blower curve is then superimposed on the system curve as shown in Figure 5-16. Blower selection will be discussed further in paragraph 5-9. A specific blower would be selected based on mechanical, electrical, and pneumatic considerations. The pneumatic considerations, discussed in this section, are of prime importance. Notice the blower curve is negatively sloped and the system curve is positively sloped. The predicted flow rate and vacuum level obviously occur at the intersection of the two curves, representing the simultaneous solution of two equations.

(e) The predicted flow rate must exceed the design flow rate to allow flow control of multi-well systems by valves located at the inlet manifold. To establish the initial system curve, the total flow rate is specified but the flow rates at the individual wells are dependent variables. However, when the SVE/BV system is operated, the system would be adjusted to achieve a specified flow rate at each well. This adjustment causes an increase in vacuum level at the blower and a decrease in the total flow rate as shown in Figure 5-16. The designer must verify that the new flow rate and pressure are within the operating range of the blower.

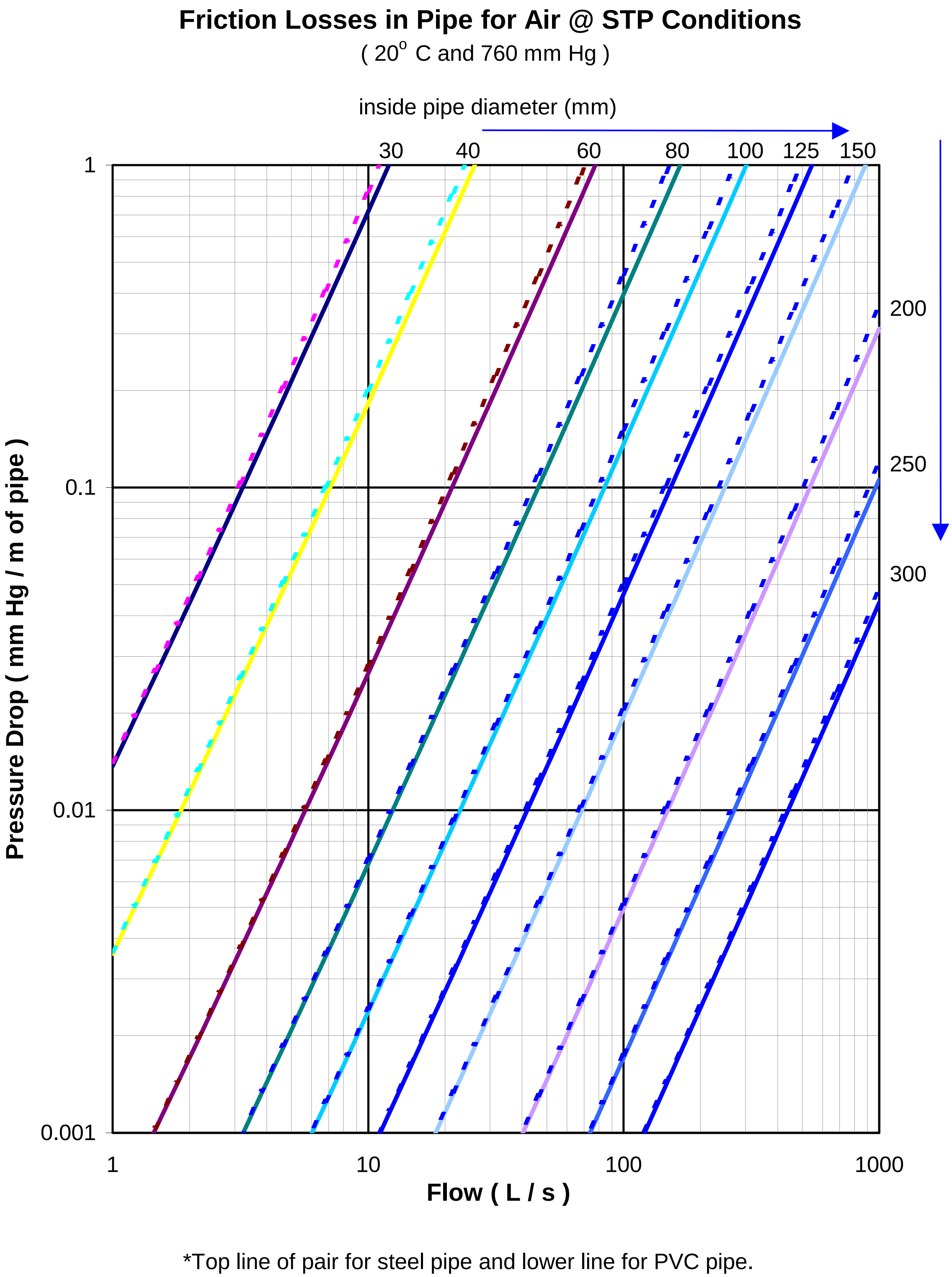


Figure 5-15. Friction Loss Chart.

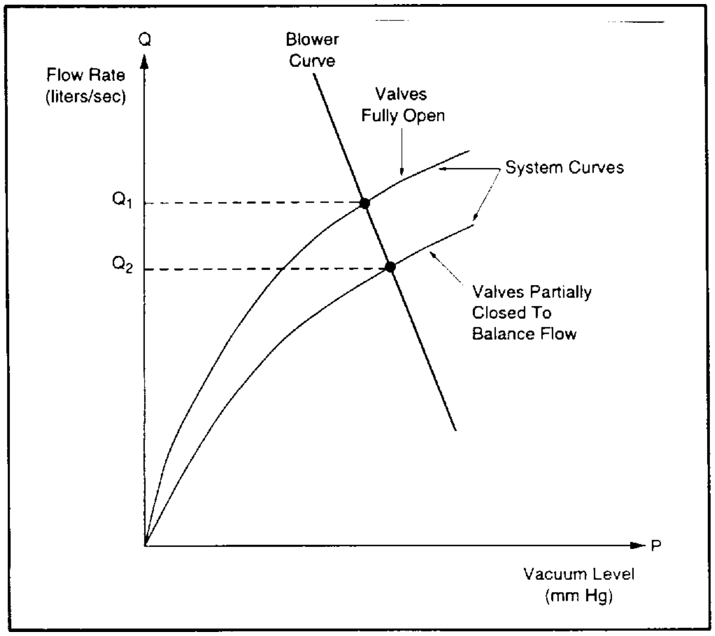


Figure 5-16. Typical SVE pneumatic analysis.

(f) This analysis demonstrates that if there are several geological units onsite with air permeabilities that differ greatly, it may be difficult or inefficient to attempt to balance the flows to a single blower. It may be worthwhile to design multiple blowers, configured in parallel. Each blower would have a blower curve that would match the associated geological unit.

b. Numerical example of pneumatic analysis. The following is a numerical example of a detailed pneumatic analysis for a network of three SVE/BV wells.

Sample Calculation - Pneumatic Analysis

This is an iterative calculation; the head loss depends on the flow but the flow rate is unknown. As described in the previous section, first, a "system" curve is developed by plotting points over the flow rate range of interest. Each point on the system curve is generated by an iterative calculation. Second, a blower is selected and the blower and system curves are solved simultaneously. Third, an analysis is performed to determine to what extent the flow rates could be equilibrated.

(1) It was assumed that the relationship for the subsurface between the flow rate and the vacuum level induced at each wellhead is predetermined. For simplicity, the following linear relationship was assumed:

$$h = aQ \tag{5-10}$$

where

a = a regression analysis coefficient. A more complex form may be chosen based either on theoretical considerations or on achieving the best fit for the empirical data

(2) Also, the piping network design (see Figure 5-17) must be established before performing this calculation. Nominal pipe sizes are usually estimated based on experience and rules-of-thumb. This aspect of the design process is also iterative. If, upon performing the pneumatic analysis, the friction losses are unacceptable, then the sizes and components of the system are altered, and the analysis is repeated.

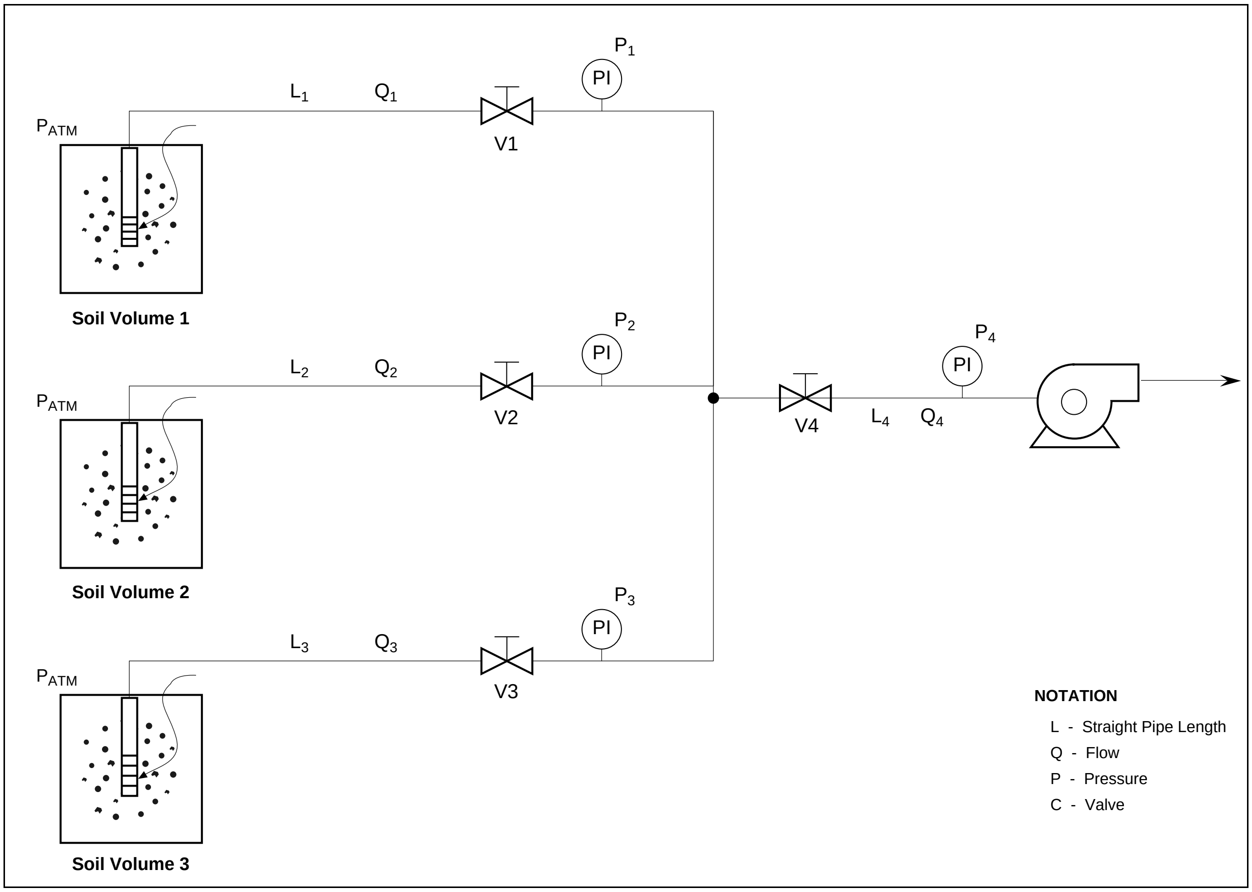


Figure 5-17. Piping network for pneumatic calculation.

(3) The spreadsheet, Table 5-1a, shows the details of the pneumatic analysis. Table 5-1a represents one point on the system curve. The density and viscosity of air were input. The total flow, Q4, and the flow in pipelines Q1 and Q2 are assumed. The flow in the last line is determined by continuity,

$$Q3 = Q4 - Q1 - Q2 \tag{5-11}$$

(4) A nominal pipe diameter was selected for each line. Consequently, the velocity and the Reynold's number Re were calculated. The relative roughness ratio, ε/D, was based on smooth steel pipe. The friction factor calculation was based on the Sacham equation:

$$f = \{-2 \log[(\varepsilon/D)/3.7 - (5.02/Re) \bullet \log[(\varepsilon/D)/3.7 + (14.5/Re)]]\}^{-2} \tag{5-12}$$

(5) To compute the frictional losses through fittings and fully opened valves, the equivalent lengths and quantities were tabulated. For each pipeline, the total length is equal to the length of the straight pipe plus the sum of the equivalent lengths (of straight pipe) of the valves and fittings.

$$L_{total} = L + \sum n \bullet L_e \tag{5-13}$$

where

n = the quantity of each fitting

L_e = the equivalent length

(6) The friction loss for an individual pipeline was calculated based on the Darcy-Weisbach equation (Equation 5-9). The total pressure loss is the sum of the pressure loss from the subsurface, the pressure loss through the system, and the pressure loss induced by closing valves.

(7) An iterative calculation was performed to develop the system curve. Notice from Figure 5-17 that all three lines merge at a single node. The pressure must be the same at this node regardless of the path. Therefore, the total friction loss must be the same through all three lines. To perform this iterative calculation, a total flow rate (Q4) was selected. Flow rate values for Q1 and Q2 are selected until all three pressure losses are equal. Then, the frictional loss through any of the three lines (h1 or h2 or h3) was added to the frictional loss in the combined line (h4) to get the total frictional loss. The results were tabulated (Table 5-1b) and the data were plotted in Figure 5-18. A blower curve was selected to match the system curve.

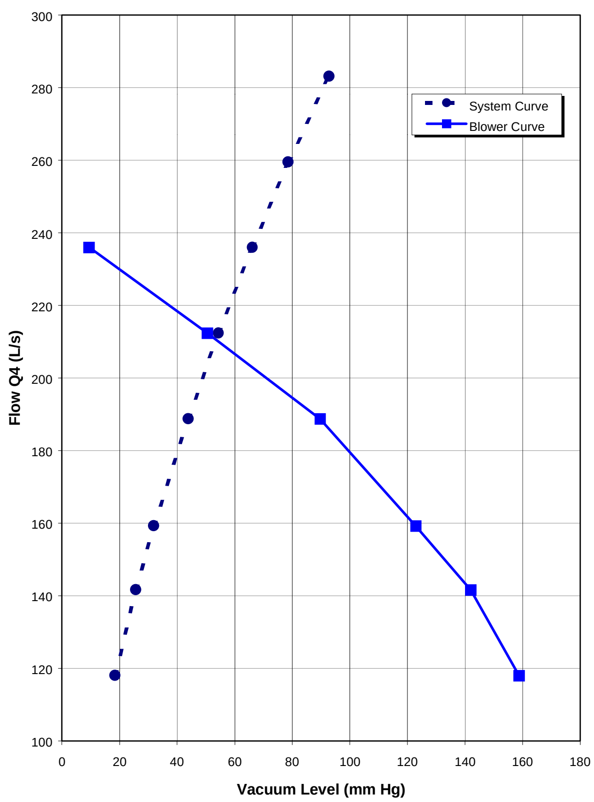


Figure 5-18. Results of pneumatic analysis.

(8) The system curve was developed assuming that the valves are in the fully open position. The final step of the analysis is to regulate the flow by closing valves. A summary of this step of the analysis is provided in Table 5-1c. Assume that it is desirable to operate each well at 64 L/s. The total flow for all three wells would be 192 L/s. By reading or interpolating the blower curve it can be determined that an 84.3-mmHg pressure loss must be induced at this flow rate. Since 10.9 mmHg are lost through line 4, lines 1 through 3 must all induce a loss of the remaining 73.4 mmHg. Recall that the pressure losses in lines 1 through 3 are identical. The surface and subsurface losses are subsequently subtracted from the total line loss to determine the pressure loss induced by closing the valve. For example, in the first line, 8.0 and 19.2 mmHg are subtracted from a total of 73.4 mmHg to obtain 46.2 mmHg. This analysis demonstrated that it is possible to achieve 64 L/s at each well.

Table 5-1a
Pneumatic Analysis for SVE System: Calculation Spreadsheet for a Single Point

Constants					
Density =	1.293 kg/m^3		(at 0 deg C)		
Viscosity =	1.71E-05 (kg/m*s)		(at 0 deg C)		
Gravity (g)	9.81 m/s^2				
	LINE 1	**LINE 2**	**LINE 3**	**LINE 4**	**COMMENTS**
Flow (L/s)	78.8	65.4	44.5	188.8	Q3 = Q4 - Q2 - Q1
Flow (M^3/s)	0.079	0.065	0.045	0.189	
Nom. Dia. (in)	4	4	4	6	Given
D [m]	0.102	0.102	0.102	0.152	Pipe ID (sch. 40)
Int. Area (m^2)	0.008	0.008	0.008	0.018	Pipe area
Vel. (v) [m/s]	10	8	6	10	v = (Q/A)
Reynolds #	7.5E+04	6.20E+04	4.2E+04	1.2E+05	Re = D*v*den./visc.
e/D	4.5E-04	4.5E-04	4.5E-04	3.0E-04	Steel pipe roughness
F	0.021	0.022	0.023	0.019	Friction factor (from eqn 5-12)
L (m)	100	250	150	50	Straight pipe length
Equivalent Lengths					
90 deg Elbow (m)	3.08	3.08	3.08	4.63	
Tee (str. thru) (m)	2.05	2.05	2.05	3.08	
Tee (Branched) (m)	6.13	6.13	6.13	9.24	
Gate Valve (m)	0.82	0.82	0.82	1.23	Fully opened
Globe Valve (m)	34.75	34.75	34.75	52.44	Fully opened
Butterfly Valve (m)	4.6	4.6	4.6	6.92	Fully opened
Expansion (m)	1.58	1.58	1.58	2	
Contraction (m)	0.82	0.82	0.82	1.4	

Table 5-1a (Concluded)

Quantities	**LINE 1**	**LINE 2**	**LINE 3**	**LINE 4**	From piping diagram
90 deg Elbow	3	4	3	2	
Tee (str. thru)	1	1	1	6	
Tee (Branched)	1	1	1	3	
Gate Valve	1	1	1	1	
Globe Valve	0	0	0	1	
Butterfly Valve	1	1	1	0	
Expansion	0	0	0	1	
Contraction	0	0	0	1	
Total Equiv. Length (m)	123	276	173	163	L + sum(L*n)
Pressure Head [meters of air]	123	196	61	111	$hf=(f*L*v^2)/(2*D*g)$
Pressure Loss [N/m^2]	1560	2480	770	1410	hf * density * g
Pressure Loss [mmHg]	11.7	18.6	5.8	10.6	N/m^2 * /133
	LINE 1	**LINE 2**	**LINE 3**	**LINE 4**	**COMMENTS**
Subsurface pneumatic losses					
Regr. Coef. (a)	300	240	680	0	From pilot study (given)
Subsurface Loss [mmHg]	23.6	15.7	30.3	0.0	h = a*Q
Pressure loss induced by closing valves					
Valve Loss	0	0	0	0	
Total Loss [mmHg]	**35**	**34**	**36**	**11**	**Surface + subsurface**

Table 5-1b
Pneumatic Analysis for SVE System: Tabulated System and Blower Curves

Q1 [L/s]	Q2 [L/s]	Q3 [L/s]	Q4 [L/s]	h1,h2,h3 [mmHg]	h4 [mmHg]	System Curve Total h [mmHg]	Blower Curve [mmHg]
47.5	30.8	39.7	118.0	14.1	4.4	18.5	158.75
57.2	36.7	47.7	141.6	19.5	6.2	25.7	141.94
64.3	41.3	53.6	159.2	24.1	7.8	31.9	122.9
76.4	49.0	63.4	188.76	33.3	10.6	43.9	89.64
85.8	55.1	71.5	212.4	41.1	13.2	54.3	50.43
95.3	61.5	79.2	236	50.1	16	66.1	9.34
105.0	67.5	87.0	259.5	59.4	19.2	78.6	
114.3	73.7	95.1	283.1	70.2	22.6	92.8	

Note: The system curve is a plot of total head versus Q4.

Table 5-1c
Pneumatic Analysis for SVE System: Summary of Analysis with Valves Partially Closed

	Line 1	Line 2	Line 3	Line 4	Blower Curve
Flow (L/s)	64.0	64.0	64.0	192.0	
Surface Loss (mmHg)	8.0	18.0	11.3	10.9	
Subsurface Loss (mmHg)	19.2	15.36	43.52	0	
Valve Loss (mmHg)	46.2	40.1	18.6		
Total Loss (mmHg)	73.4	73.4	73.4	10.9	84.3
Flow (L/s)	68.0	68.0	68.0	204.0	
Surface Loss (mmHg)	8.9	20.1	12.6	12.3	
Subsurface Loss (mmHg)	20.4	16.32	46.24	0	
Valve Loss (mmHg)	22.4	15.3	-7.1		
Total Loss (mmHg)	51.7	51.7	51.7	12.3	64

(9) Now suppose that it is desirable to operate each well at 68 L/s. A similar analysis can be performed. However, in line 3 the desired total loss could only be achieved by inducing a negative pressure loss (a pressure gain) through the valve, which is not possible. This occurs because the blower will not operate at a high enough flow rate at the predicted head loss through line 3. Therefore, 68 L/s cannot be achieved at each well.

(10) The range of flow rates that are achievable with the proposed system are bound by the following constraints:

- Continuity at the node(s).
- The operating point must be on the blower curve above the intersection of the blower curve and the system curve.
- Only pressure losses (not gains) can be induced by closing a valve.

(11) From this analysis, it is possible to show that, for the example system, the system can operate at flow rates of 64 L/s at each of three wells (192 L/s total), but it is not possible to operate at 68 L/s at each well. The system would operate at a total flow of 211 L/s (the intersection of the two curves of Figure 5-18) without equalizing the flow. Therefore, roughly 19 L/s would be lost by equalizing the flows to 64 L/s.

(12) For more complex piping networks, it would be worthwhile to acquire software designed for this application. It would also be relatively straightforward to write a computer program to automate the iterative calculation. The calculation can be reduced to solving a series of nonlinear algebraic equations simultaneously. The Newton-Raphson method is a common numerical technique accomplishing this.

(13) In summary, the pneumatic analysis was used to select a blower, determine the operating point of the system in the absence of flow regulation, and determine the effect of regulating the flow on the total flow. If the proposed treatment system or well spacing were not adequate, it would be modified. This analysis also shows the likely operating range of valves and the effects of altering piping sizes.

c. Surface considerations. Once the size of the blower has been determined, and the well configuration has been determined, a system must be provided to deal with the VOCs which reach the surface in the case of an SVE system. This concentration should be as high as possible to maximize the efficiency of the destruction system. Offgas treatment technologies are described in paragraph 5-12.

5-5. Well/Trench Construction

a. Vertical extraction wells. This section provides guidance for design and specification of vertical vapor extraction wells (Figure 5-19). Suggested sequence of specifications is provided in Chapter 6. Wells used for passive or active air injection, including BV vents, generally can be installed according to these requirements. Typical requirements are discussed under each topic.

(1) Standards. Standards for the materials and installation of extraction wells have been developed by such organizations as the American Society for Testing and Materials (ASTM), the American Water Works Association (AWWA), the American National Standards Institute (ANSI), the National Sanitation Foundation (NSF), and USEPA. A listing of the pertinent standards is provided below:

Well Construction and Materials

ASTM	F 480	Thermoplastic Well Casing Pipe/Couplings Made in Standard Dimension Ratios (SDR) Schedule 40/80, specification.
ASTM	D1785	Specification for Polyvinyl Chloride (PVC) Plastic Pipe, Schedules 40, 80 and 120.
ASTM	D 2241	Specifications for PVC Pressure-Rated Pipe (SDR-Series).
ASTM	D 5092	Practice for Design and Installation of Ground Water Monitoring Wells in Aquifers.
AWWA	A100	Water wells.
NSF	Standard 14	Plastics, Piping Components and Related Materials.
USEPA	570/9-75/001	Manual of Water Well Construction Practices.

Cement Specifications

ASTM	C 150	Specifications for Portland Cement.

Soil Classification

ASTM	D 2487	Classification of Soils for Engineering Purposes.
ASTM	D 2488	Practice for Description and Identification of Soils (Visual-Manual Procedure).

(2) Materials.

(a) Casing. New polyvinyl chloride (PVC) pipe, 100 to 150 mm (4 to 6 inches) in diameter, is normally used for SVE well casing. A reference to ASTM D 1785 or ASTM F 480 is appropriate. Larger diameters are preferred to increase flow capacity, but require larger boreholes. Assess vacuum drop inside well casing and screen diameters based on the pneumatic analysis procedures used for piping. Casing and screen diameters of 100 mm are adequate for most applications unless the formation is highly air permeable and individual well extraction rates are high (say 4 scmm or higher) in which case larger diameters may be appropriate. Other materials may be specified if contaminants, at expected concentrations, are likely to be damaging to PVC. Materials with appropriate physical properties and chemical resistance may be used in place of PVC where economical. Use heat-resistant materials such as steel if thermal enhancements to SVE may be applied at the site. PVC casing exposed to sunlight should be protected or treated to withstand ultraviolet radiation without becoming brittle. The casing must be strong enough to resist collapse at the expected vacuum levels and grout pressures. The specifications should require casing with flush-threaded joints and o-ring seals. Table 5-2 indicates a range of acceptable sizes for extraction well materials including casing.

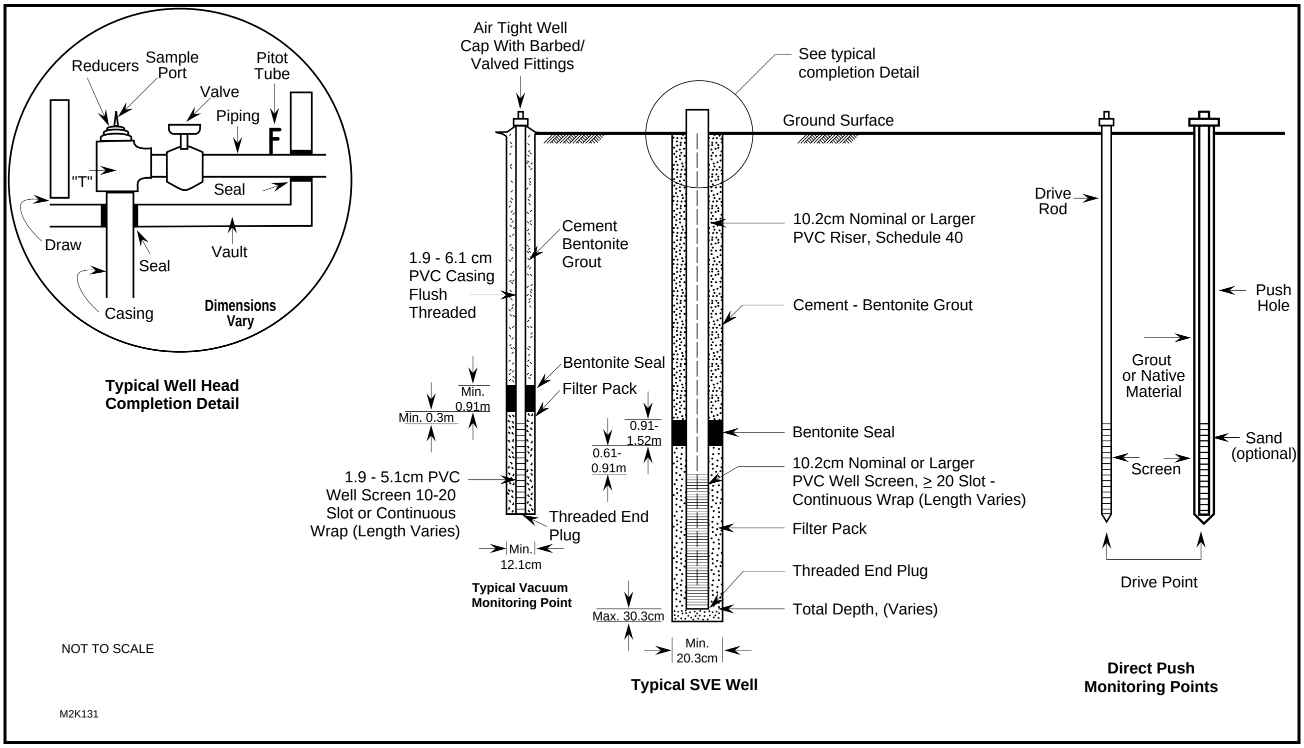


Figure 5-19. Extraction well/monitoring point construction details.

(b) Screen. Well screen is usually PVC with slotted or continuous wrap openings. Continuous-wrap screen is strongly preferred because the increased open area reduces the pressure drop across the screen and therefore reduces energy costs for the blower. Slot size is generally 0.5 mm (0.020 in.) but should be as large as possible to reduce the pressure/vacuum drop across the screen. Slot sizes of 1.01 mm (0.040 in.) or larger may be used. Larger slot sizes may, in a few cases, lead to increased entrainment of abrasive particles in the airflow. If the well will be used to recover groundwater or other liquids, the slot size must be chosen based on formation gradations, as described in Driscoll (1986). Screen with flush-threaded joints and o-ring seals are preferred.

(c) Filter pack. Pack material should be a commercially available highly uniform gradation of siliceous sand or gravel with no contaminants (chemical or physical). Choose a uniformity coefficient, C_u, of 2.5 or less. The actual gradation should generally be based on the formation grain size and the screen slot size. Coarser material may be used; however, coarser gradations may, in a few cases, lead to increased entrainment of abrasive particles in the airflow. If the well is to be used to recover liquids as well as air, the filter pack must be sized appropriately according to methods outlined in a text such as Driscoll (1986).

Table 5-2
Extraction Well Materials

Components	Operating Size Range		Comments
	Metric	English	
Casing	50 mm 100 mm 150 mm	2 inch 4 inch 6 inch	Sch 40 Larger diameters should be used where vacuum losses inside well may be high
Screen	50 mm 100 mm 150 mm	2 inch 4 inch 6 inch	Sch 40 0.5 mm or larger slots
Filter Pack	$C_u \leq 2.5$		Refer to paragraph 5-4*a*(2)(c)
Piping	50 mm 100 mm 150 mm 200 mm	2 inch 4 inch 6 inch 8 inch	Sch 40
Valves (Ball)	50 mm 100 mm 150 mm 200 mm	2 inch 4 inch 6 inch 8 inch	Sch 40
Joints (Elbow)	50 mm 100 mm 150 mm 200 mm	2 inch 4 inch 6 inch 8 inch	Sch 40

(d) Seal and grout. A well seal is necessary to prevent entry of grout into the filter pack and well screen. Unamended sodium bentonite, as pellets, granules, or a high-solids bentonite grout, is normally specified for the seal material. The seal is obviously placed above the water table and thus pellets and granules must be hydrated. A cement grout is preferred to fill the annulus above the seal to the ground surface because it resists desiccation cracking. The mixture of the grout should be specified and is normally one 42.6-kg (94-lb) bag of cement, (optionally with up to 2.25 kg of bentonite powder), with less than 18 liters of clean water. Reference ASTM C 150 in the specification as appropriate.

(e) End caps and centralizers. Flush-threaded end caps, consistent with the casing and screen in size and material, should be specified. Centralizers center the well in the borehole and must be a size appropriate for the casing and borehole. These are recommended for holes greater than 6 m deep. Select centralizers made of material that will not lead to galvanic corrosion of the casing. Stainless steel centralizers are recommended with PVC or stainless steel casing.

(f) Bioventing wells are constructed with essentially the same materials as SVE wells.

(3) Installation.

(a) Drilling methods. There are many methods for drilling. Some methods would, however, be less desirable because of the potential to smear the borehole and plug the unsaturated soils. For example, the use of drilling mud should be prohibited. Hollow-stem auger drilling is most common and is preferred.

(b) Soil sampling and logging. Sampling of soils encountered during drilling increases understanding of the subsurface and allows better decisions to be made about well construction including screen placement. Require sampling of soils at regular intervals, at least every 1.5 meters; sometimes, continuous sampling is appropriate. Samples should be obtained by appropriate method such as split spoon sampler or thin-walled tube according to ASTM D 1586 or D 1587, respectively. Sampling can also be conducted using direct push methods, if such methods are also being used for monitoring point installation. Consider sample volume requirements when specifying the sampling method. Require sampling for chemical and physical analyses be done according to an approved sampling and analysis plan. Strongly recommend a drilling log be prepared by a geologist or geotechnical engineer. Materials encountered should be described according to a standard such as ASTM D 2488. In particular, include observations of features relevant to air transmission, such as shrinkage cracks, root holes, thin sand layers, and moisture content.

(c) Borehole diameter and depth. Normally, the diameter is at least 101 mm (4 inches) greater than the diameter of the casing and screen to allow placement of the filter pack. The depth of the borehole should be based on the screen depth. The borehole should only extend to 0.3 meter below the projected bottom of the screen.

(d) Screen and casing placement. Screen and casing should be joined by flush-threaded joints and suspended in the center of the borehole. To maintain plumpness and alignment, the string should not be allowed to rest on the bottom of the hole. Centralizers should be placed on the casing at regular intervals if the depth of the well exceeds 6 meters.

(e) Filter pack placement. Filter pack should be placed around the screen to some level above the top of the screen, normally about 1 meter. Filter pack is normally placed dry by pouring down a tremie pipe. The tremie pipe, a narrow pipe with a hopper at the surface, is used to prevent bridging of grains in the annulus and is kept near the top of the pack material during placement. Store and handle the pack material carefully to avoid contamination from undesirable materials.

(f) Seal and grout placement. The grouting of the well is critical to preventing short-circuiting. Normally 1 to 2 meters of a bentonite well seal are placed above the filter pack. The specification should include a requirement for hydrating the bentonite before placement of the grout. The specification should require the addition of a volume of distilled or potable water for every 150-mm lift of bentonite pellets or granules. The bentonite should hydrate for at least 1 to 2 hours before placing the grout. This can be avoided by using a bentonite high-solids grout as the seal. Place the high-solids bentonite grout by tremie pipe. Cement grout should also be pumped into annular space via a side-discharge tremie pipe and the pipe should be kept submerged in the grout during grout placement. If the grout is to be placed to a depth of less than 4.5 meters, the grout may be poured into place directly from the surface.

(g) Surface completion. The completion of the wellhead will depend on the other features of the design, such as the piping and instrumentation requirements. An appropriate "tee" may be placed below or at grade to establish a connection with buried or aboveground piping, respectively. A vertical extension from the tee to a specified level will allow attachment of appropriate instrumentation. If finished above grade, the well may require suitable protection, such as bollards, to avoid damage to the well from traffic, etc. A well vault may be required. If a surface cover is used, the cover must be sealed around the well. In colder climates, where frost is a factor, subsurface vaults and wellheads must be protected from freezing. For this purpose, electric heat tape is frequently used for wrapping pipes and fittings. In regions of extreme cold, where electric heating is economically infeasible, extruded styrofoam insulation (which has a low moisture absorptivity) is placed over the vault. Frost will not readily penetrate directly below the insulation. Wellhead security is provided by installing vaults with padlocks. Aboveground wellheads can be enclosed within steel casings with steel caps, which can then be locked tight. In addition to sampling ports in the extraction manifold, ports should also be located on individual wellheads in order to differentiate between various extraction locations. Also, each wellhead should be fitted with both a vacuum gauge and a shutoff valve, and possibly a flow-measuring device, if individual wellhead flow rates are desired.

(h) Surveys. Establish the horizontal coordinates of the well by survey. Survey the elevation of the top of the casing if the well intercepts groundwater and the water elevation would be of interest. The accuracy of the surveys depends on the project needs, but generally is to the nearest 0.3 meter (1 foot) for the horizontal coordinates and the nearest 0.003 meter (0.01 foot) for elevation.

(i) Dual recovery. If groundwater has been impacted, the same well may be used for vapor and groundwater extraction (paragraph 3-2*d*). The screened interval should intercept the groundwater zone as well as the contaminated vadose zone. Groundwater pumps can be installed to remove the impacted groundwater and also serve to depress the water table. This will counteract the tendency for groundwater to upwell and will expose more soil to air while a vacuum is being applied within the well.

(j) Bioventing Wells. The installation techniques for bioventing wells are essentially the same as for SVE wells.

b. Soil gas/vacuum monitoring points.

(1) Materials. Generally, the same materials can be used for the monitoring points as for the extraction wells; however, there will be obvious differences in size.

(a) Casing. Generally, 20- to 50-mm (3/4- to 2-inch) diameter PVC pipe is used. Flush-threaded pipe is preferred, but for smaller diameters, couplings may be needed. Smaller diameter metallic or plastic rigid piping may also be used. Smaller diameters require less purging prior to sampling. Flexible tubing can be used as well, but is not recommended for long-term use.

(b) Screen. Either slotted or continuous-wrap screen can be specified. Slotted pipe is adequate for monitoring ports. Continuous-wrap screen is not commonly available at the smaller diameters (less than nominal 50-mm (2-inch) diameter) but can be ordered. Slot sizes smaller than those typically used for extraction wells may be appropriate for monitoring points (i.e., 0.5- to 1.01-mm or 0.010- to 0.020-inch slots). Other "screen" types can be used. Options include slotted drive points, porous points or, for short-term use, even open-ended pipe.

(c) Filter pack. Filter pack material should be appropriately sized for the screen slot width. The pack simply provides support for the screen and is not critical to monitoring point function. In some cases, no filter pack will be necessary.

(2) Installation.

(a) Drilling methods. Although a hollow-stem auger is still the primary means of installing monitoring points, direct-push methods can also be used to place slotted drive points or other vacuum/soil gas probes at specific depths. Again, mud or fluid-based drilling methods are not appropriate for this work.

(b) Soil sampling and logging. As with SVE/BV wells, it is appropriate to adequately sample the materials encountered for logging purposes and physical and chemical testing.

(c) Borehole diameter and depth. The borehole diameter should be approximately 101 mm (4 inches) larger than the screen/casing to allow placement of the filter pack. This obviously would not apply to points placed by direct-push methods. Allow adequate room for proper installation if multiport monitoring systems are to be used. Multiport monitoring systems are difficult to place and it is often more time-efficient to drill separate holes for the points at different depths in a cluster. Monitoring point depth selection is entirely site dependent, but monitoring of multiple depths within the vadose zone is recommended. It may be appropriate to extend the monitoring point into the water table to monitor water table fluctuations due to seasonal change or in response to the SVE/BV system or other remedial actions.

(d) Screen and casing placement. Casing and screen is normally placed by methods similar to those used to install SVE/BV extraction wells; however, direct-push techniques are rapid alternatives for placing monitoring points to the desired depths. Actual means of placement is dependent on the system, materials used, and site geology.

(e) Filter pack, seal, and grout placement. The procedures for sealing the well would generally be the same as those used for SVE/BV wells. Monitoring points placed using direct push techniques are subject to leakage along the drive casing or tubing if care is not taken to assure either a tight seal with the native soil after driving or in placement of the backfill/grouting of the annular space. Since the method of placement varies significantly depending on the equipment used, the project personnel responsible for the well construction must assure that the procedures used will result in a tight seal. See Figure 5-19 for typical installations using direct push methods. Use of drive points connected to the surface via flexible tubing placed loosely in the hole is not acceptable; in these cases, grouting above the screened drive point is required. Use of rigid pipe or casing is preferred. Multi-port monitoring systems require careful placement of seals between the monitored intervals to prevent "short-circuiting" between the various intervals.

(f) Surface completion. Complete the monitoring points with a suitable barbed/valved sampling port or septum attached by threaded connection to an appropriate end cap. Attach the cap to the top of the casing by an airtight connection. The points can be set above grade with suitable protection or below grade, typically in a flush-mount valve box. Each monitoring point must be clearly and permanently labeled with ID number and depth, especially any point constructed using flexible tubing grouted in a direct push hole since verifying the depth is often problematic for this type of construction.

(g) Surveys. Horizontal coordinates are necessary for each point, and vertical coordinates to the nearest 0.003 meter (0.01 foot) are necessary if monitoring the water levels.

c. Vapor extraction trench. Vapor extraction trenches are often used at sites with shallow groundwater or near-surface contamination; thus, the depth of excavation is often modest. Consider placing multiple pipes in the same trench, each with a separate screened interval, if selective extraction from various portions of the trench is required. The placement of a horizontal recovery system can be accomplished by several methods including normal excavation, trenching machines (which excavate and place pipe and filter pack in one pass), and horizontal well drilling. Figure 5-20 illustrates a typical horizontal vent well design.

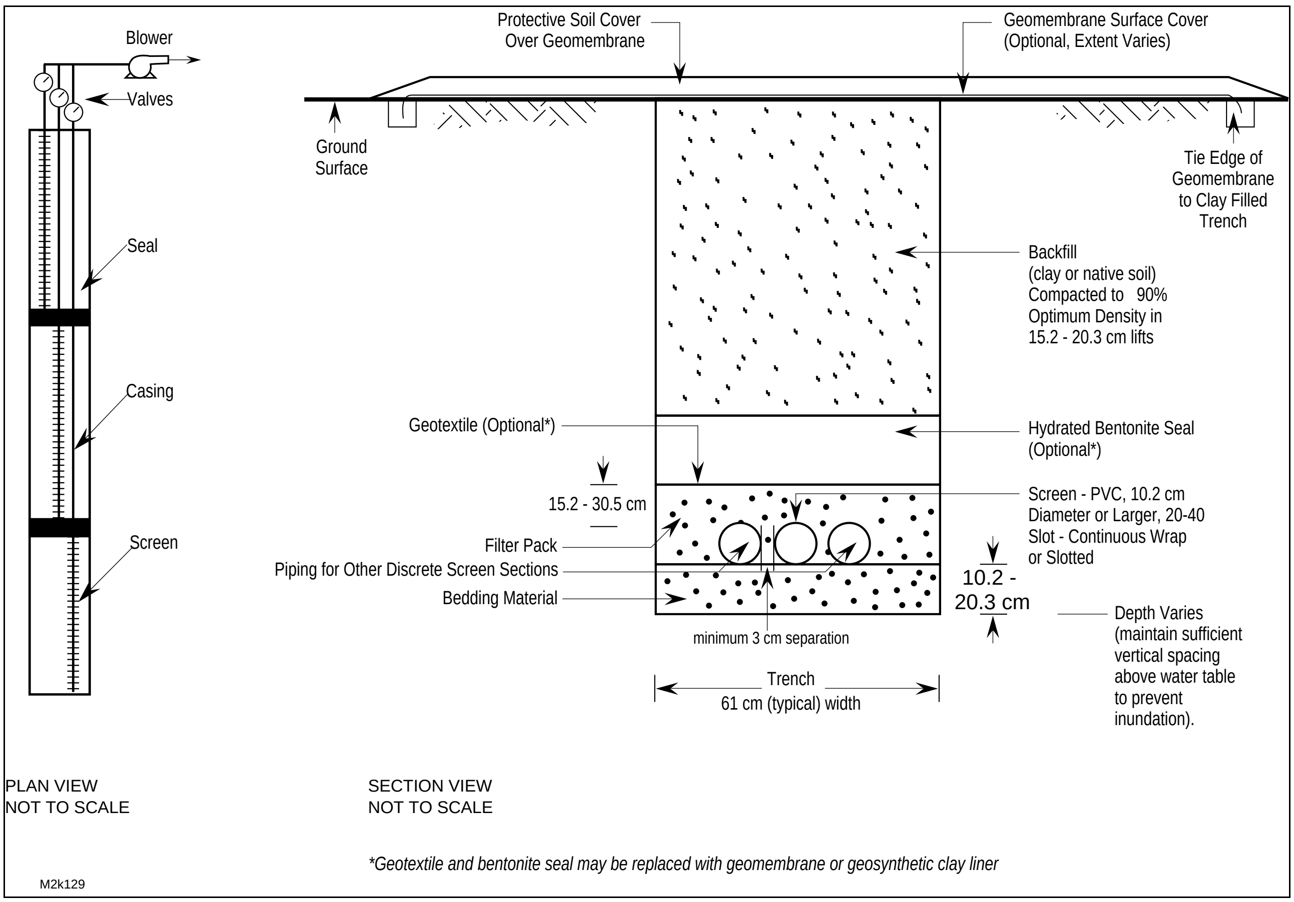


Figure 5-20. Typical horizontal vent well design, plan and section views.

(1) Materials. Materials specified for extraction trench construction are often similar to those specified for vertical wells. Different materials may be needed if specialized trenching (or drilling/jacking) methods or machines are used. Differences between horizontal and vertical applications are discussed below.

(a) Casing. Although PVC casing is commonly used, flexible or rigid polyethylene pipe may be more efficient for certain excavation methods such as trenching machines. The pipe must resist the crushing pressures of the backfill and compaction equipment. Reference appropriate ASTM standards for PVC pipe or ASTM D 3350 for polyethylene plastics pipe and fittings materials. The casing can be joined by threaded coupling or thermowelds, as appropriate for the material. Pipe sizes of 101 to 203 mm (4 to 8 inches) are often used. The actual diameter should be sized to distribute the applied vacuum uniformly along the length of the screen. This may result in use of larger diameters than typically used in vertical wells because of the potentially larger flow rates. Larger pipe sizes allow easier access for surveys and maintenance.

(b) Screen. Given the generally longer screened intervals in horizontal applications, air entry velocities are generally lower and well efficiency is less of a concern. Thus, the screen open area can be somewhat lower than is needed in vertical wells. Although continuous-wrap screen is still preferred, successful systems have also used slotted pipe. In order to provide greater degree of flexibility in control of the system where the length of trench is great (say more than 30 m), the designer should use multiple screened intervals, each connected to the blower(s) via a separate run of blank pipe. Each section of screen should be separated from the other sections through the use of trench seals composed of cement grout or clay. (Refer to Figure 5-20). If slotted pipe is specified or allowed, the specification should require a minimum open screen area. Piping and screen lengths are generally greater in trench applications and vacuum loss along the screen must be considered. Avoid using drain pipe wrapped with geotextile because of the potential for fine material to plug the geotextile. Slot size can be quite large, 1.0 mm (0.040 inch) or larger, because the lower air velocities reduce the potential for entrainment of small particles. Screen can be joined by threaded couplings or thermowelded. For some horizontal well applications, a prepacked well screen is appropriate. Prepacked screens are really two screens enclosing preselected filter pack material. The use of prepacked screen can overcome the difficulties of installing filter pack within a horizontal well.

(c) Bedding material/filter pack. Generally, the guidance for specifying filter pack in SVE/BV wells applies for trenches, but somewhat coarser material may be needed for a secure bedding for the pipe and screen. A reference to ASTM D 2321 may be appropriate. Filter material placed above the water table generally need not be sized for the formation, and can be quite coarse.

(d) Cover and seal material. Native material may occasionally be used as backfill above the filter pack in an excavated trench. Given that vapor extraction trenches are typically used at sites with shallow groundwater, low-permeability material is preferable to enhance the lateral vacuum influence of the trench. Require the use of bentonite, clay, a geomembrane, or a geosynthetic clay liner, if appropriate.

(e) Geotextile. A geotextile may be needed to separate the filter pack from native material or clay backfill in an excavated trench.

(f) Marking tape and locator strips. Specify a locator strip specifically manufactured for marking underground utilities. This tape is made of colored polyethylene backed with foil or containing embedded wire that allows others to locate the trench at later dates. This would not be applicable for drilled horizontal well installations.

(2) Installation. Installation methods vary significantly depending on excavation method.

(a) Excavation methods. Methods used to install trenches or other horizontal installations include standard earth-excavating equipment (e.g., backhoe), trenching machines, horizontal drilling techniques, and pipe jacking/microtunneling. Given this wide variety, it may be desirable to specify only the pipe, screen, pack materials, and an ultimate pipe alignment and depth. This would allow the contractor the option to propose what might be the most cost-effective method; however, the trenching technique used by the contractor must provide an adequate filter placement around the collector pipe. Note that horizontal drilling, pipe jacking, etc. reduce the amount of disturbed material and minimize both the potential for worker exposure and disruption to surface features. Many horizontal drilling techniques require drilling fluids that may not be appropriate for vapor extraction techniques.

(b) Soil sampling and logging. If open excavation techniques are used, a graphical log of the materials encountered in the trench should be prepared, including the description of the materials according to ASTM D 2488. Other excavation methods will require some log of the materials encountered at different stations and would usually be based on cutting returns from the trenching machine or drilling. Other sampling should be done as needed according to an approved sampling and analysis plan.

(c) Trench dimensions. The trench dimension should be wide enough to allow preparation of the bottom of the trench and placement of the pipe. Normally, the trench width is limited to the pipe diameter plus 600 mm. If the material to be trenched is contaminated, a smaller trench reduces the volume of material to be disposed or treated as waste. Compliance with Occupational Safety and Health Administration and USACE requirements is mandatory. If a horizontal drilling method is used, some annular space between the borehole and the screen should be required in a manner similar to vertical wells. The use of a prepacked well screen may require less annular space.

(d) Trench bottom preparation and pipe placement. The bottoms of the excavated trenches must be prepared before placement of pipe and screen. The trench must be leveled to the required grade to provide uniform bearing for the pipe. A bedding layer of filter pack material 100 to 200 mm thick should be placed and compacted before pipe and screen placement. Unstable materials should be removed. The pipe and screen should be placed in a way that prevents entrapment of filter pack or native material inside the pipe. The joining of sections of the pipe and screen must be done in a manner consistent with the material and manufacturer's recommendations. A clean-out or access port for the pipe should be provided to allow for later surveys and maintenance of the screen and casing. If the trench is to be installed to below the capillary fringe or the anticipated zone of upwelling, dewatering or dual recovery may be necessary.

(e) Filter pack placement. Filter pack placement is relatively simple in open trenches, but much more difficult in drilling or jacking operations. Compaction of the filter pack material should not be done within 150 mm to 300 mm of the pipe and screen. Some trenching machines place the pipe and filter pack material as it progresses. In these cases, it is important to verify that the machine is placing adequate filter pack around the screen. For horizontal drilling applications, various methods exist for placing filter pack, the most common and probably desirable of which is the use of the prepacked screen. The native material is allowed to collapse back upon the prepacked screen.

(f) Backfilling and compaction. The remainder of an excavated trench is backfilled with the appropriate material. Placement of a geotextile between the filter pack and backfill may be appropriate if there is a significant difference in grain size between the two materials. Backfill should be placed in 150- to 200-mm lifts and compacted to approximately 90 percent optimum standard density, determined by ASTM D 698, if cohesive materials are used. A bentonite seal can be used in conjunction with the backfill to further limit short-circuiting. A locator strip should be placed within 0.5 meter of the surface.

5-6. Piping, Valves, and Manifold System

The proper selection and specification of piping materials plays a major role in the success of SVE or BV remediation. The materials sizes and configuration of piping must be carefully planned to avoid costly operating problems, as described below. The manifold system, which is composed primarily of piping and valves, is also discussed.

a. Piping.

Piping for SVE/BV systems typically includes vacuum lines, pressure lines, sampling lines and condensate lines. Catalytic or thermal oxidizers (for offgas treatment) may also have fuel supply lines. The following major issues must be considered when designing a piping system: pressure limitations, temperature limitations, insulation, mechanical considerations, pneumatics and hydraulics, electrical grounding, and chemical compatibility.

(1) Pressure limitations: The design pressure must not exceed the maximum allowable limits for the piping system minus some reasonable factor of safety (i.e., 50 percent). Pressure relief valves should be included where required as per ANSI B31.3, Section 301.2. PVC pipe is not appropriate for uses involving high pressures (i.e., many atmospheres) because it cannot safely withstand the stresses that are imposed. However, since less than one atmosphere of vacuum or pressure is likely to ever be exerted in the context of SVE/BV, such usage appears to be well within the safe range of operation under the provision of appropriate pressure/vacuum relief. When using flexible hose lines on the vacuum side of the system, be aware that vacuum limits may be far less than pressure limits.

(2) Temperature limitations: Plastic piping, such as PVC, chlorinated polyvinyl chloride (CPVC), polypropylene (PPE), or polyvinylidene fluoride (PVDF), is commonly used for SVE/BV systems. Temperature limitations of the material must not be exceeded. Plastic piping should not be used on the blower discharge; in the event that the blower overheats, the piping may melt. Outdoor installations of non-insulated above ground plastic piping should be evaluated in accordance with a document that was produced by the Plastic Pipe Institute (PPI) entitled PPI AW-32 TR21 Thermal Expansion and Contraction of Plastic Pipe (PPI 1974).

(3) Insulation: Insulation and heat tracing can be used to prevent unwanted condensation in piping as described in paragraph 5-6. Insulate high temperature incinerator components to prevent burn hazards.

(4) Mechanical stress: The supports should be designed and spaced in accordance with ANSI/MSS SP-58, -69, -89, and -90.

(5) Pneumatics and hydraulics: Overall system pneumatics were discussed in paragraph 5-4*b*. The piping system must be sized to be compatible with the overall pneumatic scheme. In addition to considering frictional losses, it may be necessary to size the piping small enough to achieve sufficient velocity to prevent solids from settling. Velocities greater than 1.8 meters per second are recommended for pumped condensate lines.

(6) Electrical grounding: If the SVE system will handle potentially flammable organic vapors, then the designer must ensure that the piping is properly grounded. Even if an explosion-proof blower and motor

are being used, ignition of an organic-rich vapor stream it is still possible (e.g., static electricity may build up inside piping that is not grounded, and a spark may be released). Where grounding is required, conductive piping materials (e.g., steel) are usually used. In-line flame arrestors can also be used to prevent a flame from moving through piping and other equipment. When placed near potential ignition sources (e.g., thermal oxidizers), flame arrestors can be used to protect other parts of the SVE system from fire or explosion.

(7) Chemical compatibility: A list of acceptable materials is provided in Table 126.1 of ANSI B31.1. Specifically, chlorinated solvents may degrade plastic piping. Piping that will be exposed to sunlight must be UV resistant or have a UV protective coating applied.

b. Valves.

(1) Valving is utilized in SVE/BV systems for flow rate control and on/off control. A typical SVE/BV system will have a flow control valve on each extraction or injection line.

(2) The valves may be manually controlled or automatically actuated by an electric or pneumatic power source. Pneumatic actuators tend to be simpler and less costly than electric actuators particularly for explosion-proof applications. However, if a pneumatic power source is not readily available, an air compressor must be procured, operated, and maintained. Since SVE/BV systems do not typically have a large number of automated control valves and electric power is necessary for other components, electrically actuated valves are frequently employed.

(3) Most of the above considerations that apply to piping also apply to valves. The valves must be chemically compatible with the liquid or air stream; they must operate safely in the temperature and pressure range of the system; they must not create excessive frictional loss when fully opened; and in some situations they must be insulated and/or heated to prevent condensation. Also, the operating range of a control valve must match the flow control requirements of the application.

(4) The control valves must be properly sized. A flow control valve functions by creating a pressure drop from the valve inlet to outlet. If the valve is too large, the valve will operate mostly in the almost closed position, giving poor sensitivity and control action. If the valve is sized too small, the upper range of the valve will limit flow. Formulas and sizing procedures vary with valve manufacturer. Computations typically involve calculating a capacity factor C_v, which depends on the flow rate, specific gravity of the fluid, and pressure drop. The designer calculates C_v at the maximum and minimum flow rates required. The calculated range of C_v values must fall within the range for the valve selected.

(5) During the mechanical layout of the system, assure that the valves are accessible. Number and tag the valves. To avoid ambiguity, refer to the valves by number in the design and in the O&M manual.

(6) Check valves are sometimes needed between the well and the pump to prevent air from being drawn backward when the pump is shut off. Under higher vacuum, this can affect a variety of in-line readings, particularly if a carbon canister is being used for air treatment. If multiple wells are in service, each well may need a separate valve. The following is a brief description of several other valves commonly employed for SVE/BV systems (Figure 5-21):

(a) Ball valve - Also used primarily for on/off control and some throttling applications, the ball valve uses a rotating ball with a hole through the center to control flow.

(b) Butterfly valve - Used for both on/off and throttling applications, the butterfly valve controls flow with a rotating disk or vane. This valve has relatively low friction loss in the fully open position.

(c) Diaphragm valve - A multiturn valve used to control flow in both clean and dirty services. The diaphragm valve controls flow with a flexible diaphragm attached to a compressor and valve stem.

(d) Needle valve - A multiturn valve used for precise flow control applications in clean services, typically on small diameter piping. Needle valves have relatively high frictional losses in the fully open position.

(e) Globe valve - Used for on/off service and clean throttling applications, this valve controls flow with a convex plug lowered onto a horizontal seat. Raising the plug off the seat allows for fluids to flow through.

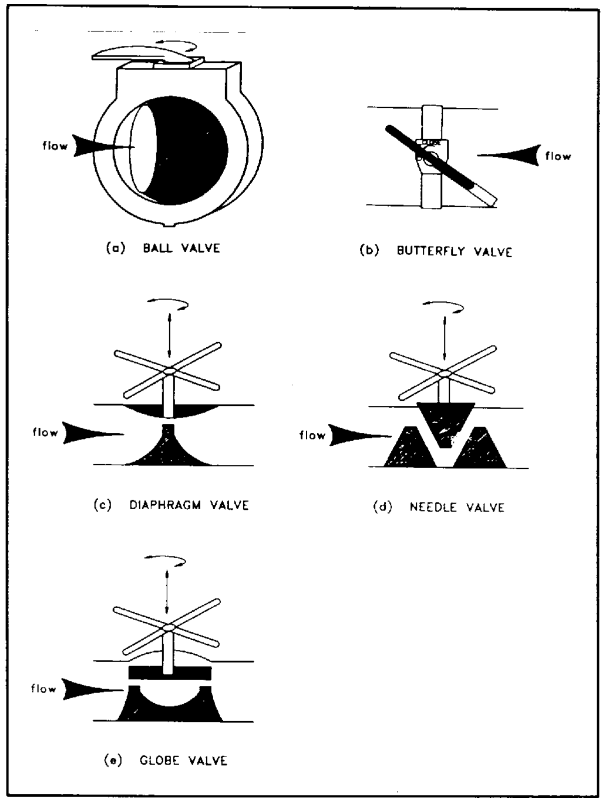


Figure 5-21. Valve schematics.

c. Manifold system design.

(1) A manifold system interconnects the injection or extraction wells into a single flow network prior to being connected to the remainder of the SVE/BV system (refer to Figure 5-22). A manifold system will include a series of flow-control valves, pressure and airflow meters, and VOC sampling ports at each wellhead, and these devices may be grouped in one central location for convenience. The manifold system is typically constructed of PVC, high density polyethylene (HDPE), or stainless steel.

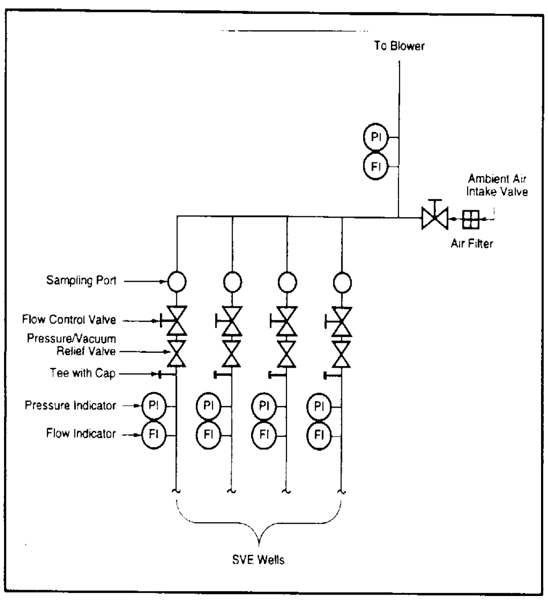


Figure 5-22. Typical manifold system.

(2) The manifold system should also have a manual air control valve to bleed fresh air into the SVE/BV pump system to reduce vacuum levels and temperatures within the motor/blower. Air control valves also control the applied vacuum in the subsurface and are used to start the vacuum system from a condition of zero applied vacuum. These valves should be of a type which will permit

adequate control of the airflow (globe, butterfly, needle, or ball valve designs work well). Also, a pressure/vacuum relief valve may be included in the manifold to protect the piping.

(3) The number of tees and joints within the pipe runs from the extraction wells to the manifold system should be minimized to reduce piping head losses. Angles within the solid runs should be kept above 135 degrees to reduce any air or vacuum restrictions within the pipe chases.

5-7. Condensate Control

a. Need for control. Condensate controls are often necessary for SVE/BV systems to prevent unwanted liquids from accumulating in piping, blowers, or air emission control devices. The condensate controls remove moisture and store the liquid prior to disposal.

b. Causes of condensation. The soil vapors extracted from the subsurface are typically at or near 100 percent relative humidity. A subsequent decrease in temperature or increase in pressure will cause condensation. This condition is frequently encountered under winter conditions, or at any time or location that the aboveground piping is cooler than the temperature in the portion of the subsurface through which the gas has passed. Also, in cases where the water table is close to the surface or when a perched water table is present, water droplets may become entrained in the vapor stream, or free water may be drawn into the air-water separator. Piping between the vent wells and the blower should be sloped toward the vapor/liquid separator ("knockout") to prevent condensate from collecting in the piping.

c. Overall design considerations. The following paragraphs discuss (1) the effects of condensation on the overall design, (2) a method for estimating condensate generation, and (3) design issues involving air/water separators and condensate collection.

(1) Condensate control relates in various ways to the overall design of an SVE/BV system and needs to be considered not just with respect to the design of the condensate control devices. For a long-term SVE/BV system the best approach is often to minimize condensation by assuring that the relative humidity of the vapor stream does not exceed saturation, in which case, depending on cost, the SVE/BV system components could be located in a heated building (paragraph 5-14). A building heated to 20 °C would be sufficient. The lateral lines connecting the wells to the inlet manifold should either be buried or heat traced and insulated. Due to inefficiencies in converting electrical energy to mechanical energy, a vacuum blower will significantly heat the air stream, thereby lowering the relative humidity. This "thermal boost" should be considered and taken advantage of in the design of the SVE system.

(2) It is necessary, based largely on condensate control considerations, to decide whether to locate the blower upstream or downstream of activated carbon equipment if activated carbon is included in the design for offgas treatment. Ideally, the air flowing through the carbon would have a relative humidity of 40% at 27°C and low pressure. Lower temperatures thermodynamically favor adsorption of organics because adsorption is exothermic. However, a reduction in temperature increases the relative humidity. Generally if the blower is located upstream of the carbon, a small temperature rise (e.g., a rise of 5-15°C) would be favorable because of humidity reduction, but a large temperature rise (i.e., a rise of 50°C) would be unfavorable for thermodynamic reasons cited above. In addition to condensate control issues, the designer must also consider the pressure limitation of the vessels and the capacity of the blower. Since there is an absolute limit to the amount of vacuum that can be created and significant head loss can occur in the carbon vessel, it may be preferable to locate the carbon downstream of the blower. Also, most carbon vessels will

be able to withstand greater positive pressure than vacuum, which would also argue for locating the carbon downstream of the blower.

(3) For short-term installations and pilot studies, it may not be practical to keep the system heated in order to avoid condensation. In those cases, air/water separators must be adequately sized to collect the moisture. For pilot units operating in the winter, it is worthwhile and typically necessary to insulate carbon vessels. In general, the air/water separator should be kept as cool as possible to generate condensation and the downstream system components should be kept warm through insulation and/or heat tracing.

d. Condensate quantity estimation. Prior to designing an SVE/BV system or conducting a pilot study, the engineer should estimate the rate at which condensate will be generated. An estimate can be obtained by using psychrometric charts which are readily available in standard thermodynamic references, as shown in the sample calculation below:

Sample Calculation - Condensate Quantity

Estimate the rate of condensate generation for a 2-day pilot study conducted during the winter using a 236 L/S (500 CFM) SVE system. The average ambient temperature will be 272 K and the absolute pressure in the air/water separator will be 0.5 atm.

Assume air is extracted at 100% relative humidity and 286 K. From a psychrometric chart,

Conc. of water vapor = 8.86×10^{-3} kg/kg air (at 286 K)

Conc. of water vapor = 3.43×10^{-3} kg/kg air (at 272 K)

Subtracting, Condensate = 5.43×10^{-3} kg/kg

Use the Ideal Gas Law to estimate the air density.

Density = PM/RT = (0.5 atm) $\times$ (29 kg/kg-mole) / (0.0821 L-atm/ g-mole K) $\times$ (272 K) $\times$ (1,000 g-mole/kg-mole)

Density = 6.49×10^{-4} kg/L

where M = 29 kg/kg-mole

The flow rate times the concentration of the condensate in the air (based on the air density in the piping) yields:

(5.43×10^{-3} kg/kg) $\times$ (6.49×10^{-4} kg/L) $\times$ (236 L/s) $\times$ (86,400 s/day) $\times$ (1 L/kg) = 71.9 L/day (19 gal/day)

Therefore, 144 liters would be generated in 2 days. Supply one 55-gallon drum to store condensate for the pilot study. This allows for an additional 64 liters (17 gallons) due to entrainment.

This example demonstrates that significant volumes of condensate can be generated even in short-duration pilot studies.

e. Design aspects of air/water separation.

(1) This manual will be concerned solely with physical- or inertial-type air/water separators. These are the types most commonly used for SVE/BV systems. It is possible (although not typically practical) to use refrigerated air dryers or regenerative desiccant dryers. Refrigerated dryers remove moisture from air by chilling the air to the point where water condenses to a liquid and drains away. Regenerative desiccant dryers adsorb water vapors in a desiccant such as anhydrous sodium sulfate or activated alumina. Inlet air is dried in one vessel while desiccant is regenerated in another vessel. Although not typically used for SVE/BV applications, these types of dryers should be considered if highly effective moisture removal is required.

(2) Inertial separators are generally used for air/water separation in SVE/BV systems. By imparting centrifugal force to the water droplets, these separators can collect small water particles. Typically particles as small as 20 microns can be removed. The gas stream is injected into a cylinder through a tangential inlet to create a vortex and the gas stream is expelled through the top of the cylinder. This vortex forces water particles to the outside wall where they settle to the bottom by gravity.

(3) Manufacturers of inertial air/water separators typically size the units according to flow rate. A detailed discussion of centrifugal separation can be found in Perry's Handbook (Perry and Green 1984). Pressure drops through the separator can be approximated by the following empirical equation (Corbitt 1990). This equation assumes a rectangular inlet.

$$F = KB_c H_c / D_e^2 \quad (5\text{-}14)$$

where:

F =cyclone friction loss expressed as fraction of velocity head

K =an empirical constant, typical value = 16

B_c =gas inlet width (m)

H_c =gas inlet height (m)

D_e =gas outlet diameter (m)

$$\text{Head loss} = F\,(V^2/2g) \quad (5\text{-}15)$$

(4) The condensate separator should be able to withstand the highest vacuum that a blower is capable of exerting. Condensate separators need pumping systems or a manual method to remove the separated water. Pumps must be both leakproof and able to provide sufficient head to offset the vacuum in the separator vessel. Condensate treatment and disposal methods are discussed in paragraph 5-13.

5-8. Particulate Filters

a. Particulate filters are typically installed between the condensate removal system and the blower inlet. Although the condensate removal system will decrease the concentration levels of airborne particulates, the removal efficiency may not be sufficient. High particulate levels may cause operational problems with the blower, downstream piping, or offgas treatment equipment. Particulate air filters should be employed to remove airborne particles down to the 1- to 10-micron range.

b. Cartridge air filters are often used for this type of application. Filter elements are manufactured from a variety of elements including pleated paper, felt, or wire mesh. Paper elements are inexpensive and typically disposable. Felt and wire mesh filters may be washed. The filter is selected based on the airflow rate, the desired removal efficiency, and pressure drop. Pressure gauges, or a single differential pressure gauge, should be installed upstream and downstream of the filter. Filters should be changed when indicated by the pressure difference across the filter.

5-9. Blower Silencers and Acoustics

a. Depending on the size of the blower and the location of the SVE/BV system, inlet and outlet silencers may be necessary to reduce blower noise. Blowers present two noise problems: (1) pulsation within the piping system, and (2) noise radiation from the blower itself. Pulsation noise peaks can be severe for large blowers and can result in noise discharges in the high decibel range.

b. Silencers are selected based on flow capacities and noise attenuation properties. These devices typically contain chambers with noise absorptive elements. Silencer manufacturers should provide the designer with an attenuation curve, which is a plot of noise attenuation (decibels) versus frequency (hertz). The objective is to obtain the greatest noise reduction in the range of sound frequencies emitted by the blower.

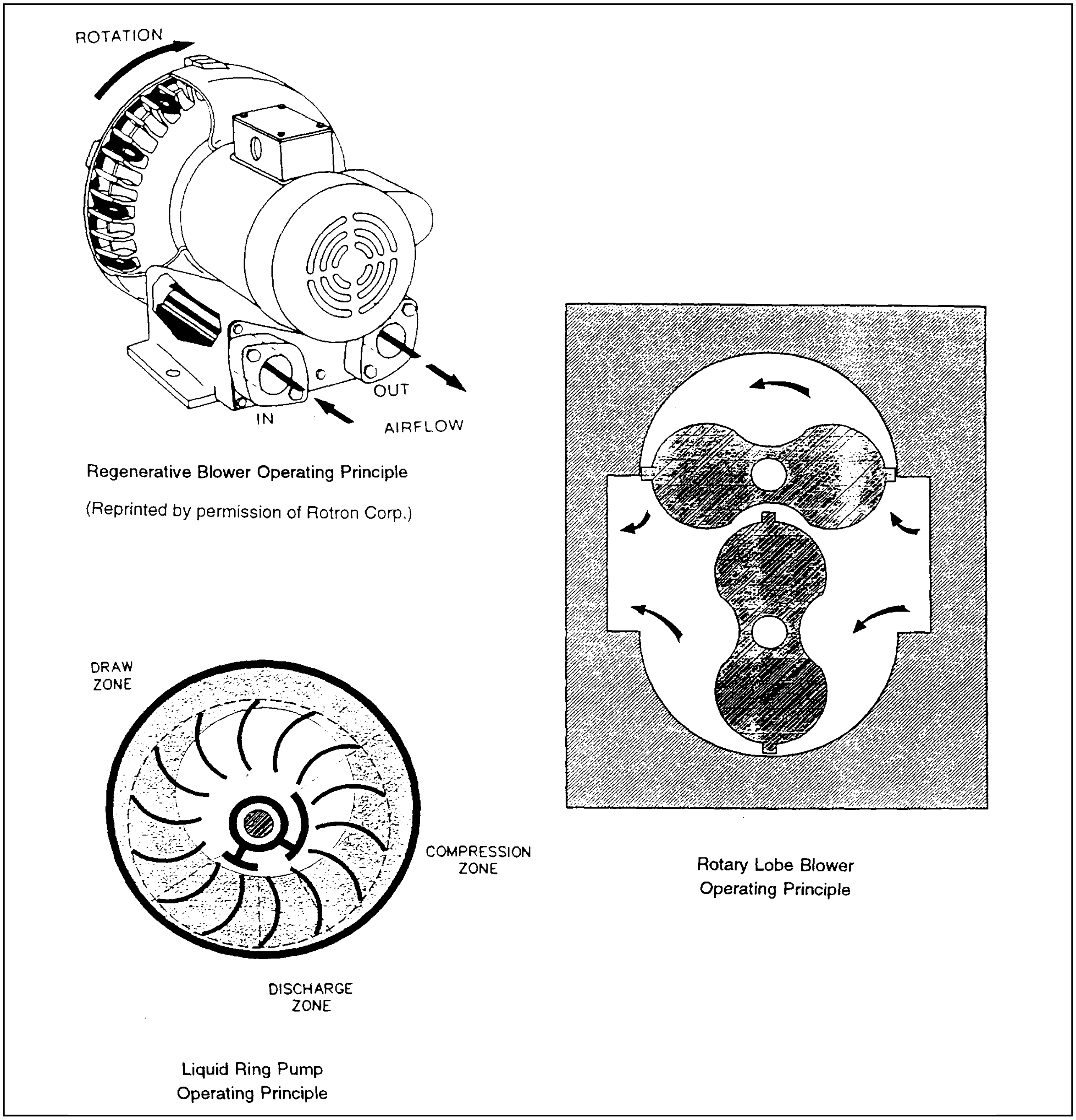
c. Also, if the SVE/BV system is located within a building, shed, or trailer, wall material selection should consider acoustical properties. Complete tables of absorption coefficients of various building materials versus frequency may be found in books on architectural acoustics.

d. Address site specific hearing protection requirements in the site safety and health plan. Refer to Section 05.C of EM 385-1-1 for USACE hearing protection and noise control requirements. Require the contractor to measure sound pressure levels in work areas near noisy equipment. Ensure the contractor enrolls employees with potential exposure in excess of 85dB(A) (TWA) in a hearing conservation program meeting 05.C.03 requirements and that employees with exposure in excess of 90 dB(A) are provided with hearing protection or are protected by administrative (time limitation) means.

5-10. Blowers and Vacuum Pumps

The pneumatic considerations involved in blower selection have been discussed in paragraph 5-4*b*. The following paragraphs focus primarily on mechanical considerations and the interrelationships among the blower design variables.

a. Mechanical categories of blowers. This section will describe the following three types of blowers commonly used for SVE/BV systems: regenerative blowers, rotary lobe blowers, and liquid ring vacuum pumps, which are shown schematically in Figure 5-23. These blower types are most applicable for low, medium, and high vacuum applications, respectively. Although there are many blowers that could possibly be used for SVE/BV systems, these three types are representative of those frequently encountered. Vendors will typically have several models of the same blower series, each with a different flow capacity. All three of these blower types are generally available in flow rate ranges required by SVE/BV systems -- 80 m^3/hr (47 cfm) to 8,000 m^3/hr (4,700 cfm). Variable speed blowers should also be considered for use at sites where the flow rate required will decrease with time.



Regenerative Blower Operating Principle

(Reprinted by permission of Rotron Corp.)

Rotary Lobe Blower Operating Principle

Liquid Ring Pump Operating Principle

Figure 5-23. Blower schematics.

(1) Regenerative blowers. These blowers are typically employed for SVE/BV applications requiring less than 203.2 cm (80 inches) of water vacuum. Regenerative blowers are compact and produce an oil-free airflow. The principle of operation is as follows: A multistage impeller creates pressure through the use of centrifugal force. A unit of air enters the impeller and fills the space between two of the rotating vanes. The air is thrust outward toward the casing but then is turned back to another area of the rotating impeller. This process continues regenerating the pressure many times until the air reaches the outlet.

(2) Rotary lobe blowers. These blowers are typically used for a medium range of vacuum levels (roughly 51 to 457 cm or 20 to 180 inches of water). During operation of these blowers, a pair of matched impellers rotate, oriented in opposite directions, trap a volume of gas at the inlet and move it around the perimeter to the outlet. Rotation of the impellers is synchronized by timing gears which are keyed into the shaft. Oil seals are required to avoid contaminating the air stream with lubricating oil. These seals must be chemically compatible with the site contaminants. When a belt drive is employed, blower speed may be regulated by changing the diameter of one or both sheaves or by using a variable speed motor.

(3) Liquid ring vacuum pumps. A liquid ring vacuum pump transfers both liquid and gas through the pump casing. Centrifugal force acting on the liquid within the pump causes the liquid to form a ring around the inside of the casing. Gas is trapped between rotating blades and compressed by the liquid ring as the gas is forced radially inward toward a central discharge port. After each revolution the compressed gas and accompanying liquid are discharged. Vacuum levels close to absolute vacuum (i.e., absolute pressure equals zero) can be generated in this manner. These pumps generate a waste stream of liquid that must be properly disposed of. The waste stream can be reduced by recycling the liquid; however, a cooling system for the liquid stream may be required to avoid overheating the pump.

b. Design criteria.

(1) Typically, the airflow rate is specified and the vacuum level is determined based on pneumatic calculations (see paragraph 5-4*b*). Based on conservation of energy, once flow rate and pressure are specified the horsepower requirement becomes a dependent variable and cannot be uniquely specified.

(2) Frequently, the designer will specify a flow rate and vacuum level and then select a motor based on vendor-supplied blower curves. However, it is possible to predict the required power as follows:

$$\text{power (watts)} = [\text{mass flow rate (kg/s)}] \times (g = 9.81\,\text{m}/s^2) \times [\text{change in head (m)}] / \text{efficiency} \qquad (5\text{-}16a)$$

or

$$\text{power (hp)} = [\text{mass flow rate (lb/s)}] \times [\text{change in head (ft)}] / ([\text{efficiency} \times 550\,\text{ft}\cdot\text{lb/sec}\cdot\text{hp}) \qquad (5\text{-}16b)$$

(3) The efficiency term must account for both the power loss within the blower due to mechanical and pneumatic friction and the motor efficiency at converting electrical energy to mechanical energy. The change in head across the blower is calculated by using Bernoulli's equation.

Example - Blower Selection

Select an SVE blower to operate at a flow rate range of 142 to 189 L/s and a vacuum level of 56 mm Hg. The vapors may contain up to 500 ppm of trichloroethylene.

To meet these requirements a regenerative blower with the following performance curve was selected:

Flow (L/s)	94.4	118	142	165	189	212	235
Vac. (mm Hg)	82.1	76.5	70.9	65.3	57.8	50.4	41.0

Notice that this blower can provide 189 L/s at 57.8 mm Hg. Use a spark-proof aluminum housing and seals and gaskets made of viton to be compatible with trichloroethylene.

According to manufacturer's information the blower is equipped with a 7.46-kW (10 hp) Class 1, Group D motor. A 220-volt/3-phase power supply was available at the site. Based on the power requirements, the site power, and data supplied on a motor wiring chart, 28 full load amps (FLA), an 80-amp fuse or a 50-amp breaker are required. The chart also specifies using a minimum of 8 gauge wire and thermal overload protection. Based on manufacturer's information, the maximum noise level is 81 db at 60 hertz; therefore, provide an inlet and an outlet silencer.

(4) The power loss within the blower causes a temperature rise in the air stream. The goal of the engineer in specifying a blower (or pump) is often to select a blower that is the most efficient within the desired operating range of flows and pressures, thereby minimizing power loss. This is often a difficult task for SVE/BV systems given the uncertainty associated with predictions of subsurface airflow.

(5) At the beginning of the system operation, higher flows may be needed, requiring greater blower capacity. But as the project progresses, the flow rates may decrease as wells are closed off or as BV replaces SVE (see paragraph 5-2*a*.) To create flexibility, consider employing a single variable-speed blower or multiple blowers with good turn-down capabilities. However, the range of speeds on some variable speed blowers may not be adequate. For example, the efficiency of rotary lobe blower decreases with changes in speed. SVE/BV systems should also have ambient air intake valves which (among other things) can regulate flow from the subsurface by adjusting the ratio of ambient air to soil vapor while keeping total flow to the blower relatively constant. This type of flow adjustment avoids overheating the blower and maintains the blower within the proper operating range. However, the power requirements are not reduced as soil vapor flow rate is reduced, and contaminant concentrations in the offgas are reduced, decreasing offgas treatment efficiency. In situations such as this, reducing the blower size may be advisable to minimize the intake of ambient air and to maximize system efficiency.

(6) Blowers and other electrical motor driven equipment (including wiring) must be designed and constructed in accordance with National Fire Protection Association (NFPA) 70, with proper consideration given to environmental conditions such as moisture, dirt, corrosive agents, and hazardous area classification. If flammable organic vapors may potentially flow through the blower, then the designer must ensure that the blower internals are constructed of non-sparking materials; also placement of flame arrestors in piping, near the blower, should be factored into the design.

c. Tanks and vessels. Pressure vessels and storage tanks must be designed, constructed, tested, certified, and inspected as noted below:

(1) Atmospheric tanks must be designed to operate at pressures from atmospheric to 3.5 kPa (0.5 psi).

(2) Petroleum, hydrocarbon, or flammable product tanks, as part of the implementation of an SVE/BV system, may be needed to store flammable products. There are some systems, such as those with liquid-phase carbon and onsite carbon regeneration, which recover pure product from the vapor stream. The thermal treatment of offgases often utilizes a fuel source, such as propane, which must be stored onsite. Also, some SVE/BV projects may have an associated groundwater and/or free-product extraction component; thus, free-product would be recovered directly from the subsurface.

(3) The tanks for storage of hydrocarbon products, especially flammable products, need to be designed, installed, and specified in accordance with NFPA Standards. Product storage tanks must include secondary containment with the capacity to contain in excess of the tank volume. Product storage tanks must also be equipped with double-walled piping (if piping is buried), vents, level switches and indicators, overflow alarms, and fire extinguishers. In accordance with Federal and local fire codes, tanks containing flammable products must be located at prescribed distances from buildings, property lines, and sources of ignition.

(4) Storage tanks for SVE/BV systems are most frequently aboveground storage tanks. If below-ground tanks are employed, the tanks must be double-walled and include leak detection. Tanks must be designed and constructed in accordance with the following standards:

UL-142 Shop Fabricated Aboveground Tanks

UL-58 Underground Tanks

UL-80 Oil Burner Fuel Tanks

API-650 Field Erected Tanks

(5) Tanks storing in excess of 11,000 liters of VOCs are not recommended, but if necessary, must be designed in accordance with 40 CFR, Part 60.

(6) Low pressure tanks (3.5-103.5 kPa or 0.5-15 psi) are designed to operate at pressures above 3.5 kPa (0.5 psi) but at less than pressures specified in the ASME Boiler and Pressure Code, Section VIII, Division 1.

d. Structural design considerations. When determining the design load for a foundation, consider the stability factor and the results of the soil report in the analysis. Consider uplift, dead loads, live loads, wind, seismic, snow, thermal, crane, hoist, vehicle, and operating loads. Foundation design requires the consideration of underlying soil stability conditions.

Wind loads: Apply to full projection of all equipment, tanks, skids, and platforms in accordance with ANSI Standard A58.1 or local building code if more stringent.

Seismic load: Estimate in accordance with ANSI Standard A58.1 or local building code if more stringent.

Live load: Consider the combined total weights of all equipment when full.

Anchorage: Design to resist lateral forces.

5-11. Instrumentation and Process Controls

In the design of an SVE/BV system, a good deal of attention must be paid to the instrumentation and control system. A good instrumentation and control system design will assure that the individual components are coordinated and operate effectively. This section will present the instrumentation and control elements used in an SVE/BV design, different degrees of automation, a list of minimal acceptable components, and a description of special instrumentation that may be used in SVE/BV systems.

a. Description of design elements. A full SVE/BV design will include, at a minimum, the following elements:

(1) P&I diagrams. Piping and instrumentation diagrams show the interrelationship between process components, piping and process control devices. ISA and ANSI standards (ANSI/ISA-S5.1) govern the preparation of P&I diagrams. These diagrams show all major process components organized according to process flow. The instrumentation symbols are shown in “bubbles.”

(2) Electrical wiring diagram. This diagram shows the wiring of all physical electrical devices, such as transformers, motors and lights. If appropriate, the diagram is organized in ladder logic form. See Figure 5-28 for an example.

(3) Description of components. The specifications must include a description of instrumentation and control components including installation and mounting requirements.

(4) Sequence of control. The sequence of control must be included in both the design submittal and the operation and maintenance manual. Control information concerning system start-up, system shutdown, and response to malfunctions must be included.

(5) Control panel layout. A control panel layout must be designed. This drawing will show, to scale, all electrical components and the associated wiring. Depending on the project, this control item may be submitted as a shop drawing by the instrumentation and control contractor.

(6) Logic diagram. A logic diagram must be included if the process control logic is not apparent from the P&I diagram. This diagram shows the logical (and, or, nor, if-then) relationships between control components but does not show interconnecting process flow. For example, the diagram may show that if switch #2 is placed in the on position and there are no alarm conditions, then the blower will turn on and activate a green indicator light.

(7) Legend and standard symbols. The set of documents must have a legend to explain the symbols that are used. Regardless of the existence of the legend, standard symbols must be used wherever applicable.

b. Degrees of automation. The degree of automation is generally dependent on the complexity of the treatment system, the remoteness of the site, and monitoring and control requirements. Typically, there is a trade-off between the initial capital cost of the instrumentation and control equipment, and the labor cost savings in system operation. Providing automated instrumentation and control systems can reduce the time an operator needs to be on site and, therefore, operations cost. A cost / benefit analysis should be performed to determine the degree of automation. Relatively high labor costs and a short payback period can often be used to justify some level of automation. Some degree of automation is generally recommended for systems anticipated to remain in operation for more than 12 months. For SVE/BV systems, the four major operational parameters that require control are:

- Liquid collection. The condensate collection system accumulates liquid that may overflow. Liquid level indicators, switches, and alarms are required.

- Pressure/vacuum. Blowers may require vacuum breaking controls to protect the motor units. The system may also require pressure relief valves to protect tanks or vessels.

- Flow rate. Flow rate monitoring is essential to judge the progress of the SVE/BV remediation effort. Flow control is required to balance multi- well systems.

- Temperature. Temperature control may be necessary to prevent motor overload on pumps and blower, prevent carbon bed fires, or safely operate catalytic or thermal oxidation systems.

(1) Generally, there are three forms of process control: local control, centralized control, and remote control. In a local control system, all control elements (i.e., indicators, switches, relays, and motor starters) are located adjacent to the associated equipment. In a centralized control system, the control elements are mounted in a single location. These systems may include a hard-wired control panel, a programmable logic controller (PLC), or a computer. Remote control can be accomplished several ways including by means of modems or radio telemetry.

(2) To select the appropriate control scheme, the advantages and disadvantages of each control scheme must be considered. A localized control system is less complex, less expensive, and easier to construct. For example, if a level switch in a tank is controlling an adjacent discharge pump, it would obviously be simpler to wire from the tank directly to the adjacent pump than to wire from the tank to the centralized control panel and then from the panel back to the pump. As the control system becomes more complex, it becomes more advantageous to locate the control components in a central location. Centralized control systems are also easier to operate. Centralized data acquisition and control may include the use of computers or PLCs. Automated process control is a complex topic that is beyond the scope of this manual; however, several points are worth considering. The greater the number of control inputs, the more worthwhile it is to utilize computer or PLC control. For SVE/BV systems, the inputs may include signals from level indicators, flow meters, pressure switches, or thermocouples. The threshold for utilizing PLCs or computers is generally between five and ten inputs, depending on the type of input and operator background. Often plant operators will be more familiar with traditional hard-wired control logic than with control logic contained in software. However, process logic that is contained in software is easier to

change (once you learn the software) than hard-wiring. Therefore, if extensive future modifications to the proposed system may be anticipated, hard-wiring the process logic should be avoided.

(3) Modems and radio telemetry can be used to control these systems remotely. Radio telemetry is typically used over shorter distances when radio transmission is possible. Modems are used with computerized control systems.. Systems can include automatic control, shutdown sequences, and a telephone dialing and reporting system that will call operators when systems reach critical points or shutdown. In addition to basic control devices, sophisticated systems that allow for remote collection of performance data are available. The process control industry has adopted the term, supervisory control and data acquisition (SCADA), to describe a collection of computer, communications equipment, sensors and other devices that interface for remote monitoring and control of complex treatment systems. Once again, considerations such as site location, capital cost, standardization, operator background, and system complexity govern the selection of these devices.

c. Minimum acceptable process control components. At a minimum, the following process control components are required:

- Pressure/vacuum and flow indicators for each well, of the appropriate range for anticipated conditions.
- Blower motor thermal overload protection.
- Vacuum relief valve or vacuum switch to effect blower shutdown.
- Sampling ports before and after air treatment and at each wellhead.
- Pressure and temperature indicators, as well as flow control valves and pressure relief valves at blower inlet and outlet.
- High level switch/alarm for condensate collection system.
- Explosimeter - for sites with recently measured LEL levels greater than 10 percent.
- For catalytic or thermal oxidizers,
- Automatic burner shutoff
- Temperature monitoring and control
- Interlock with SVE control system
- UL listed burners and fuel train

d. Special instrumentation. There are several specific instruments that are common to SVE/BV systems that should be considered in the design. These instruments include oxygen / carbon dioxide meters, explosimeters, organic vapor analyzers, and process gas chromatographs (GCs).

(1) Oxygen / carbon dioxide meters. Used to monitor oxygen and/or carbon dioxide levels of soil gas withdrawn from vadose zone monitoring points, as an indicator of microbial respiration (see Chapter 3). Oxygen data is especially important for determining if air is being adequately distributed through areas of

concern during BV. Can also be used to monitor oxygen and/or carbon dioxide levels of air withdrawn via SVE systems.

(2) Explosimeter (or combustible gas indicator). May be used on sites where high VOC levels cause a potential explosion hazard. These meters must be equipped with relays to automatically shut off process component or dilute the air stream with ambient air. Catalytic combustion is the detection principle for most of these devices. Explosimeters should not be used unless oxygen monitoring is also being performed. Explosimeters can produce false readings if the level of oxygen falls below the minimum level required for the instrument to function properly. Organic vapor analyzers (e.g., FIDs), calibrated to the proper hydrocarbon component can also be used to determine if vapor levels are approaching the LEL; and do not require concomitant oxygen monitoring.

(3) Organic vapor analyzers. Can be used to monitor vapor phase VOC discharges. Units with flame ionization, photo-ionization, thermal conductivity, electron capture, or infrared detectors are typically employed (i.e., FID, PID, TCD, ECD or IR), depending on the compounds of interest. Process units (as opposed to the handheld units frequently used for environmental work) can be rack or panel mounted and equipped with control relays.

(4) Process GC. Some SVE/BV systems utilize GC-FID for onsite monitoring and control. Several vendors manufacture GCs that can be automated for process monitoring and control; however, laboratory facilities (to prepare standards, etc.) and trained chemists are also required for GC monitoring.

5-12. Electrical Systems Planning

This section establishes the basic requirements for materials, equipment, and installation for electrical systems. The need for electrical systems planning must be recognized. All basic considerations that will affect the overall design must be reviewed at the beginning of the design phase. The electrical systems planning should include any future power needs that might be anticipated. The design philosophy must emphasize the following in addition to technical and statutory needs:

- Safety of personnel and equipment.
- Flexibility for expansion.
- Accessibility for operational and maintenance needs.

a. Codes, standards, and specifications. The following is a list of applicable reference codes, standards, and specifications. The latest revisions shall be used.

American Petroleum Institute (API)

RP500A Recommended Practice for Classification of Areas for Electrical Installations in Petroleum Refineries

RP500B Recommended Practice for Classification of Areas for Electrical Installations at Drilling Rigs and Production Facilities on Land and on Fixed and Marine Platforms

RP500C Electrical Installations at Petroleum and Gas Pipeline Transportation Facilities

National Fire Protection Association (NFPA)

30 Flammable and Combustible Liquids Code

70 National Electrical Code

496 Purged and Pressurized Enclosures for Electrical Equipment in Hazardous Locations

497 Class I Hazardous Locations for Electrical Installations in Chemical Plants

Institute of Electrical and Electronics Engineers (IEEE)

C.2 National Electrical Safety Code

141 Recommended Practice for Electrical Power Distribution for Industrial Plants

518 The Installation of Electrical Equipment to Minimize Electrical Noise Inputs to Controllers from External Sources

b. Area classifications.

(1) Classifications.

(a) The electrical equipment shall be selected and installed in accordance with the requirements of the classifications of the various areas involved in the SVE/BV system.

(b) The areas to be classified fall into one of the following types as established for electrical installations in the National Electric Code (NEC):

- Class I, Group D, Division 1.
- Class I, Group D, Division 2.
- Unclassified.

(2) Definition of areas.

(a) All control rooms, battery rooms, and switch houses shall be designed as unclassified areas, although battery rooms require venting to prevent hydrogen gas buildup above the LEL. Where these rooms are located within or adjacent to a hazardous location (i.e., an area that may potentially have an explosive atmosphere) the rooms shall be pressurized in accordance with NFPA 496. All such pressurized rooms shall be provided with means of egress directly to the outside without passing through the hazardous area. Where this is not practicable, a suitable single door system shall be installed. Installation of double airlock-type door systems is discouraged.

(b) Areas shall be physically separated from each other, and classified as Class I, Division 1; Class I, Division 2; or unclassified. These classifications are as defined in the NEC. Unclassified zones will be maintained at a higher pressure than Division 2 zones, and Division 2 zones higher than Division 1 zones in order to prevent hydrocarbon vapors from migrating into areas containing ignition sources. Differential pressure switches with alarms will be installed between adjacent fire zones where assurance of a positive differential pressure between fire zones with different classifications is required.

(c) Classification of an area as Division 1 or Division 2 requires careful consideration of the process equipment in that area, the physical characteristics of hazardous liquids/gases, the amount of ventilation provided to the area, and the presence of various equipment such as piping with valves, fittings, flanges, and meters. The volume and pressure of the gases or liquids involved in the process should also be considered.

(d) The classification of Class I hazardous locations as Division 1 or Division 2 is not a straightforward task. The NFPA has developed a recommended Practice (NFPA 497) which should be followed.

(3) Application of area classification.

(a) Hazardous locations exist in many areas of a facility where flammable liquids or gases are processed. It is important that all of these locations be identified and equipped with appropriate electrical equipment to ensure safety of personnel and the facilities. There are three basic questions to be answered in classifying a location:

- Will there be flammable gases or liquids stored, handled, or processed within or adjacent to the location?
- What is the likelihood that a flammable concentration of gases or vapors will collect in the atmosphere of the location?
- Once determined to be hazardous, how far could the hazard possibly extend?

(b) In discussing flammable gas/air mixtures, a knowledge of vapor densities and liquid volatility is important. Vapor density indicates whether a gas is heavier or lighter than air. Lighter-than-air gases released in an open area will often dissipate rapidly because of their low relative density. Classification based on heavier-than-air flammable gases is normally conservative when compared to lighter-than-air gases or vapors.

(c) The likelihood of a release of sufficient quantity of flammable substances to form an explosive mixture depends upon the equipment, containers, and/or piping system containing the gas or liquids. It depends upon the presence of valves, compressors, pumps, or meters that could possibly leak. It also depends upon the ventilation available to carry the gas or vapors away.

(d) The extent of the hazardous area is determined by the presence of walls or barriers and air currents that may carry the gas or vapors away from the point of release.

(4) Adequate ventilation. For the purposes of area classification as outlined in this practice, the definition of "adequate ventilation" is established as follows:

(a) Open structures: An adequately ventilated location is any building, room, or space which is substantially open and free from obstruction to the natural passage of air through it, vertically or horizontally. Such locations may be roofed over with no walls or may be closed on one side (NFPA 497).

(b) Enclosed/partially enclosed structures: Adequate ventilation, as defined in NFPA 30, is that which is sufficient to prevent accumulation of significant quantities of vapor-air mixtures in concentrations over one-fourth of the lower flammable limit (LFL). API RP500B considers a mechanical ventilation system capable of providing a minimum of twelve air changes per hour in all parts of the process area as adequate and as having met the intent of the NFPA Code.

(5) Class I, Division 1, locations may be distinguished by an affirmative answer to any one of the following questions:

- Is a flammable mixture likely to exist under normal operating conditions?
- Is a flammable mixture likely to exist frequently because of maintenance, repairs, or leakage?
- Would a failure of process, storage, or other equipment be likely to cause an electrical failure simultaneously with the release of flammable gas or liquid?
- Is the flammable liquid or vapor piping system in an inadequately ventilated location, and does the piping system contain valves, meters, seals, and screwed or flanged fittings that are likely to leak significant volumes in proportion to the enclosed space volume?
- Is the zone below the surrounding elevation or grade such that flammable liquids or vapors may accumulate?

(6) Class I, Division 2, locations may be distinguished by an affirmative answer to any one of the following questions:

- Is the flammable liquid or vapor piping system in an adequately ventilated location, and is the piping system (containing valves, meters, seals, and screwed or flanged fittings) not likely to leak?
- Is the flammable liquid or vapor being handled in an adequately ventilated location, and can liquid or vapor escape only during abnormal conditions such as failure or rupture of a gasket or packing?
- Is the location adjacent to a Division 1 location, or can vapor be conducted to the location as through trenches, pipes, or ducts?
- If positive mechanical ventilation is used, could failure or abnormal operation of ventilating equipment permit mixtures to build up to flammable concentrations?

(7) Outdoor installations, usually consisting of open pipeways, are adequately ventilated and do not justify a Class I, Division 2, classification because only a catastrophic failure would result in an explosive concentration of gas or vapor. However, each specific case must be reviewed carefully before a classification is assigned.

(8) All area classification tasks should consider long-term planning such as future changes/modifications that may be made on the system being designated.

(9) Unclassified locations.

(a) Locations that are adequately ventilated (including most outdoor installations) where flammable substances are contained in suitable, well-maintained closed piping systems which include only pipe, valves, fittings, and flanges, are considered nonhazardous. Most outdoor open pipeways are considered nonhazardous. Areas which are not ventilated, provided the piping system is without valves, fittings, flanges, or similar appurtenances, are also considered nonhazardous.

(b) Locations containing permanent sources of ignition, such as fired boilers, pilot lights, equipment with extremely high surface temperatures (above the ignition point of the gases in the area) are not deemed hazardous when considering electrical installations, because the electrical equipment would not be the primary source of ignition.

(10) Electrical conduits. The configuration of the electrical system will be site-specific, but some general guidelines can be followed.

- Electrical duct runs shall be designed by electrical engineers and reviewed by civil engineers for structural competence.
- Buried ducts may be installed in trenches or on fill. Permanent ducts will use concrete encasement.
- Trenching and backfilling procedures shall conform to standards provided by a civil engineer. Selected backfill shall be placed to a height above the top of the duct that will prevent damage from traffic or other surface loading.
- Existing overhead power lines should be of concern during the design phase of the project. Power lines may obstruct or create hazards during the installation of wells, equipment, and buildings.

(11)Lighting.

(a) Lighting fixtures shall be arranged, maintaining required space-to-height ratio, for even lighting and minimum glare. Lighting specifications will also be based on electrical area classification (i.e. explosion-proof systems may be required).

(b) Emergency lighting should be provided for all egress points and critical areas in the event of a power failure.

(12)Motors.

(a) Motors shall conform to the latest applicable requirements of NFPA National Electrical Code (NEC) and NEMA. Motor enclosures are specified for the area in question. Open drip-proof (OPD) motors are not usually used for SVE/BV systems. Outdoor SVE/BV systems require weatherproof motors. As a minimum, totally enclosed, fan-cooled (TEFC) motors are used. The classification of the area will determine the need for explosion-proof motors. It is only motors with a totally-enclosed-explosion-proof (TEXP) rating that are rated for both outdoor and explosive atmospheres. Motor with only an explosion-proof (X-P) rating require appropriate cover when being used outdoors.

(b) In hazardous areas, motors shall be temperature rated “T2C” where the “T” rating is as defined per Table 500-2C of the NEC (NFPA 70). Refer to NFPA 497M - 1983 for temperature requirements for motors. If the hazardous products differ from the above, a more restrictive “T” rating may be required.

(13) System voltage. Unless otherwise specified, electrical equipment shall be designed for operation at the utilization voltage listed in Table 5-3.

(14) Packaged equipment. Several items may be purchased as packaged equipment completely engineered and fabricated by the supplier. Such items may require electrical supplies and interface, or tie-ins, with other systems. Electrical distribution and control system drawings shall show all these requirements as subsystems with references to supplier's detailed drawings. Design, inspection, and acceptance of packaged equipment shall be approved by a recognized approval authority such as Underwriters Laboratories or Factory Mutual.

(15) Heat tracing system.

(a) Electrical heat tracing shall be provided for pipes and equipment where close temperature control is necessary and as required for process and operational needs. All electric heat tracing equipment and accessories must be approved by a recognized approval authority such as Underwriters Laboratories or Factory Mutual. Impedance-type heat tracing is not acceptable. Electrical heat tracing must consider the area classification (e.g., Class I Division 2).

(b) Design, engineering, and installation criteria shall be per information detailed in NFPA NEC Article 427.

(c) The presence of electrically heated pipelines and/or vessels shall be made evident by the posting of appropriate caution signs or markings on pipelines approximately 3 meters apart on alternating sides of the pipe.

(16) Fire protection.

(a) The installation shall consist of process and utility units that are subdivided into fire zones. The delineation and classification of fire zones in all units shall comply with the provisions of the NEC (NFPA 70).

Table 5-3
Utilization Voltages

Service	Utilization Voltage	System Nominal Voltage
Motors below ½ HP	115 v, 1-Phase, 60 Hz 208 v, 1-Phase, 60 Hz	120 v 240 v
Motors ½ HP to 200 HP	460 v, 3-Phase, 60 Hz 230 v, 3-Phase, 60 Hz 200 v, 3-Phase, 60 Hz	480 v 240 v 208 v
Lighting	115/200 v, 3-phase, 60 Hz,4-wire 460 v, 3-phase, 60 Hz, 3-wire 460/265 v, 3-phase, 60 Hz,4-wire	120/208 v 480 v 480/277 v
Noncritical instruments; power and control; telephone equipment	115 v, 1-phase, 60 Hz	120 v
Telecommunication equipment	48 v DC	-
Shutdown systems, alarms, Instrumentation	24 v DC with battery backup	-
Critical loads that do not permit Interrupt	120 v, 1-phase, 60 Hz	-
Switchgear control	125 v DC	-
Heat tracing	265/460 v, 3-phase, 60 Hz 115 v, 1-phase, 60 Hz	277/480 v 120 v

(b) Fire zones shall be protected by two types of detection systems:

- A hydrocarbon gas-detection system employing primary gas detectors calibrated for methane and supplemental detectors calibrated for propane and heavier gases.
- A fire detection system employing thermal, ionization, and ultraviolet detectors.

(c) Each fire zone shall be protected by an independently controlled ventilation system and an independently controlled fire extinguishing system approved for the specific application. The fire extinguishing system shall be designed to operate both automatically and manually.

(d) All installations shall be in compliance with NFPA Standards and the approval of local fire and electrical inspectors. No piping component that may eventually leak shall be installed above electrical equipment. Such components include screwed fittings (not seal welded), flanged joints, and any type of valve.

(e) Some permanent SVE treatment systems have installed sprinkler heads inside the carbon vessels for fire protection. A heat detector may or may not be included to activate the fire suppression system. Otherwise a fire department connection may be sufficient to allow spraying of water on the carbon.

5-13. Summary of Offgas Treatment Methods

a. Offgas treatment methods will be discussed in this section. A complete discussion of the engineering design of air emission control devices is beyond the scope of this manual and would duplicate information in other USACE documents. This section will primarily emphasize those aspects of the offgas treatment methods that will impact the overall design of the SVE system. Offgas treatment alternatives are summarized in Table 5-4.

(1) Offgas treatment methods need to be able to cope with a potentially wide range of volatile chemicals and concentrations to prevent exposure of the surrounding area to the VOC for which the SVE or BV process is designed. The initial concentrations of VOC can range from less than 100 ppmv to percent concentrations (over 10,000 ppmv), and the treatment system must operate properly for these ranges as well as those encountered near the end of the remediation process; i.e., a few ppmv. Thus a system design must consider concentrations ranging over several orders of magnitude. The consequences of the treatment process itself (e.g., oxidation) must also be considered in selecting the materials of construction. Disposal of residuals such as spent carbon must also be addressed.

(2) The following data are required by designers of offgas treatment equipment: initial and long-term concentration ranges; complete analysis of the influent gas; total flow rate range; required removal efficiency; availability of utilities; required degree of control, monitoring, and automation. Communication between the designers of the subsurface and aboveground components is essential.

b. Brief description of technologies. The technologies most often used for SVE offgas treatment are briefly described below.

(1) Vapor phase carbon can remove many classes of organic compounds including aromatics, aliphatics, and halogenated hydrocarbons. Many SVE systems utilize granular activated carbon in flow-through reactors. Properly designed, these systems are relatively simple to operate. Adsorption is due to chemical and physical attractive forces between liquid or gas phase molecules and the molecules of the solid adsorbent. Activated carbon is commonly manufactured from raw materials such as wood, coal, coke, peat, and nut shells.

(a) A carbon adsorption design usually includes multiple adsorbers, in which case the columns are operated either in series or in parallel. The series arrangement is generally operated so that the secondary acts as a backup when breakthrough occurs on the primary canister. When the lead column is removed from service, the lag column is moved up to the lead position and the new column (or regenerated column) is installed in the lag position. The pressure / temperature ratings of the carbon vessels must exceed the anticipated operating conditions of the SVE system equipment.

(b) Adsorption is normally a reversible process; that is, under suitable conditions the materials that have accumulated in the carbon can be driven off and the carbon can be re-used. Thermal reactivation is the most widely used regeneration technique. In SVE systems where carbon usage is low, onsite regeneration will not be cost-effective and the spent carbon should be either disposed of or regenerated offsite. For larger long-term SVE systems, onsite regeneration should be considered. The decision to regenerate onsite would be based on a complete life-cycle cost economic analysis. The concentration threshold for considering onsite regeneration is typically between 50 and 500 ppm for a project duration of several years. If possible, the designer should estimate the total carbon usage for the life of the project and compare the carbon cost with the capital and O&M cost of the regeneration system. A similar economic analysis could be performed for comparison with catalytic and thermal oxidation, as discussed below.

(c) As mentioned previously, carbon becomes less efficient with high relative humidity. Activated carbon relies on an extensive network of internal pores to provide surface area for adsorption. Although there is not direct surface attraction, the water vapor occupies internal pore space due to capillary condensation. The optimum sorption conditions occur when the air flowing through the carbon has a relative humidity of 40% at 27°C at a pressure near atmospheric. At a site where the extracted air is 10°C, a relatively small increase in the temperature caused by the vent blower (e.g., 5-15°C) will generally improve carbon efficiency by reducing the relative humidity, but a large temperature increase (e.g., 50°C) would impair to the carbon sorption efficiency. However, in the winter, a larger temperature increase at the same site might be desirable for more efficient sorption. A heat exchanger or chiller could be used to moderate the temperature.

(2) Activated carbon is the most widely used adsorbent material; however, other adsorbent materials include alumino-silicate crystal structures known as “zeolites”, as well as synthetic polymers. Selection of an appropriate adsorbent material is primarily a function of the contaminant to be adsorbed. Non-polar or low-polar molecules with a higher molecular weight typically adsorb well to carbon, while polar molecules would be better sorbed by zeolites or specialized polymer resins. Activated carbon has the lowest initial cost. In addition, the wide range of pore sizes of activated carbon makes it useful for a wider range of contaminants than either zeolites or polymers. Conversely, the adsorption capacity of activated carbon is relatively low and can be adversely affected by the relative humidity of the gas stream. Zeolites and polymers are expensive; however, they each have much higher adsorption capacities than activated carbon. The need to replace zeolites is rare and polymer replacement occurs only slightly more often than with zeolites. These alternate sorbents are usually regenerated to recover solvents or other materials, saving on

disposal costs, somewhat offsetting their high capital costs. Polymers are also hydrophobic materials and thus their adsorption capacities are substantially less affected by humidity than activated carbon.

(3) Thermal Oxidation. There are four general types of thermal oxidation systems available for controlling VOC emissions. These include: 1) Direct Flame Thermal Oxidizers (DFTO); 2) "Straight-Through" Flameless Thermal Oxidizers (FTO); (3) Regenerative Thermal Oxidizers (RTO); and, 4) Catalytic Oxidizers (Cat-ox). Each type of system operates somewhat differently, however, the primary goal of thermal oxidation is to raise the temperature of the gas stream to a sufficient level to promote oxidation (or combustion) of the contaminant to CO_2 and H_2O. The heat for thermal oxidation comes from heat input to the oxidizer in the form of supplemental fuel (either gas or electric) as well as from the BTU content of the VOCs in the SVE vapor streams. In-line flame arrestors should be incorporated into the design when using thermal oxidizers. Placed just upstream of thermal oxidizers, flame arrestors can prevent fire from moving through piping, and protect other parts of the SVE system from fire or explosion General guidelines for which type of thermal oxidation system is most appropriate for a site are provided in Figure 5-24.

(a) Significant cost savings can be realized by utilizing heat recovery techniques. Some thermal oxidation systems are “recuperative”, using a heat exchanger to capture a portion of the heat of combustion and preheat the influent stream prior to oxidation in the combustion chamber. Recuperative systems can recover up to 70% of the heat of the oxidizer effluent (USEPA, 1995c), and therefore require substantially less supplemental fuel to operate. Primary heat recovery exchanges heat from the air exiting the combustion chamber with the air entering the combustion chamber. Secondary heat recovery uses the heated exhaust to preheat plant air or produce steam. As with all heat exchange systems, there is a trade-off between heat recovery efficiency and the size, or more precisely the surface area, of the heat exchanger.

(b) Thermal oxidizers are capable of treating waste streams with virtually any VOC concentration assuming stochiometric or excess oxygen levels are present. However, they are generally designed to treat a specific waste stream with a specific mass loading (i.e. mass of contaminant per unit of time). Variations in the mass loading due to changes in concentration require variations in the amount of auxiliary fuel (or dilution air if mixture is too rich) added to the oxidizer, but do not substantially affect the degree of treatment.

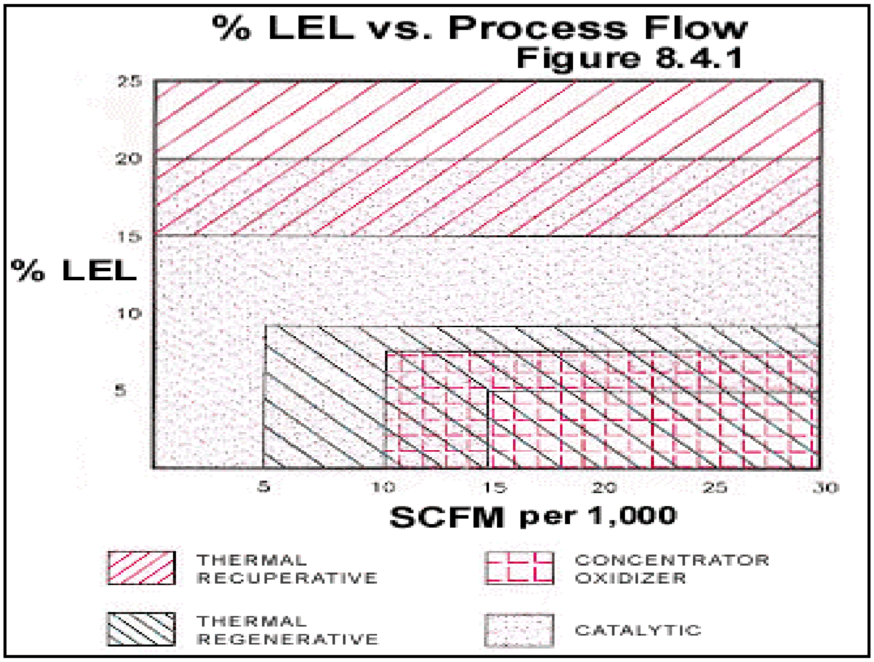


Figure 5-24. Applicability of thermal oxidation systems based on percent LEL influent concentration and process flow rate (from Rafson, 1998).

(c) Catalytic oxidation is the most common means of thermal offgas treatment for SVE systems. The catalyst lowers the activation energy of the oxidation reaction allowing it to proceed at a lower temperature, usually between 300 and 900 °F. The lower combustion temperature results in significant energy savings. Catalyst manufacturers typically claim 95 percent or greater conversion of non-methane hydrocarbons. The most common catalysts for VOC oxidation are precious metals, usually either platinum or palladium supported on ceramic or stainless steel monoliths (honeycombs). Metal oxide catalysts such as chromium oxide, aluminum oxide, copper oxide and manganese oxide can be used to effectively treat chlorinated VOC (CVOC) vapors (USEPA, 1995c). Catalytic oxidation of CVOCs has become well established in the past couple of years and several vendors are offering this as off-the-shelf technology. The treatment of fluorinated compounds (e.g. freons) is more challenging, but can also be achieved although the catalyst may need to be replaced/reactivated more frequently. A complete catalytic oxidation system may include a burner, a heat exchanger, the catalytic reactor, and a stack.

(d) Catalytic oxidation is subject to several limitations. The following contaminants are known catalyst deactivators and contribute to shortened catalyst life: lead, mercury, zinc, arsenic, antimony, copper, tin, iron, nickel, chromium, sulfur, silicone, and phosphorus. Catalytic oxidizers will overheat if the fuel content of the SVE air stream is too high. This should be considered at sites where the vapor levels exceed 10 percent of the lower explosive limit. Under favorable conditions, catalysts need to be replaced approximately every three years.

(e) Catalytic oxidation of halogenated hydrocarbons generates acidic vapors. Recent advances in catalyst technology have resulted in catalysts that are resistant to halogenated compounds. However, the acid emissions require treatment. Consequently, scrubbers are typically installed in such systems. Scrubbers are described in a later section.

(f) A common concern associated with the use of catalytic oxidation of extracted vapors containing chlorinated compounds is the potential generation of products of incomplete combustion (PICs) and/or toxic breakdown products, including chlorinated dibenzo-p-dioxins (CDD or "dioxin") and chlorinated dibenzofurans (CDF). PICs are formed during thermal oxidation when there is insufficient oxygen, temperature and mixing of the vapor stream to support complete oxidation. Most commercial incineration systems are designed to have sufficient fuel/air mixing processes and temperature so that the formation of PICs during thermal oxidation is minimized (USEPA 1997c). EPA describes two primary scenarios for the formation of CDD/CDFs during combustion processes:

1. Formation of CDD/CDFs during combustion from precursor compounds, which are chlorinated aromatic hydrocarbons having a structural resemblance to the CDD/CDF molecule.

2. Formation of CDD/CDFs in the ductwork downstream of the combustion chamber as the treated stream is cooled (referred to as *"de novo"* synthesis).

According to Alley and Associates Inc. (1998), the following additional conditions must also be present for dioxin formation:

- Temperatures between 300°F and 700°F
- The presence of particulate matter in the waste gas.

The most common precursor compounds extracted by SVE systems are chlorobenzenes and chlorophenols (EPA, 1997). Because SVE produces contaminated vapors only (as opposed to combustion of solid materials), the necessary particles are not likely to be present in SVE off-gas streams as adsorption sites for the formation of CDDs and CDFs. Thus, the scenarios described above do not appear to be applicable to SVE applications. Dioxin formation has been reported on projects where catalytic oxidizers were used to treat off-gas from SVE systems. At one Superfund site, low concentrations of dioxins were reportedly generated during catalytic oxidation of an offgas stream that contained vinyl chloride as the primary contaminant. However, an equipment blank for this sampling event contained more dioxin than the offgas sample, casting doubt on the formation of dioxin.

(g) Extensive field testing for the formation of CDD and CDF from SVE thermal oxidation units has apparently not been performed. Limited CDD/CDF testing was performed on a catalytic unit being used on an SVE system at Edwards Air Force Base (EAFB), California to treat soil contaminated by petroleum hydrocarbons and CVOCs. Laboratory analysis of influent and effluent samples to the catalytic unit showed much lower CDD and CDF concentrations in the system effluent stream than in the influent stream. Ambient air samples were also obtained from locations upwind and downwind of the catalytic unit. These results revealed that the concentrations of CDDs and CDFs were much higher at the upwind location than at the downwind location (Buck 2000). Based on the results of the sampling performed at EAFB, CDD and CDF compounds do not appear to be produced from catalytic oxidation of contaminated vapors from the SVE system at this site. A collaborative review of the EAFB results was performed by Dr. B. J. Lerner, of Oakmont, PA. Based his review, Dr. Lerner concluded that the results were not unexpected due to the absence of iron oxides or fly ash in the system effluent to act as sorption sites for dioxin formation.

(h) Non-Catalytic thermal oxidation involves heating the air stream to a temperature high enough for combustion. Non-Catalytic thermal oxidizers typically operate between 1,200 and 2,000°F. They are generally simpler and more versatile than catalytic systems because there is no need to be concerned with compatibility of the compounds with the catalyst. For SVE applications, thermal units are generally economical for the initial stages of operation and as long as concentrations remain high, however they are less efficient as concentrations decline, because supplemental fuel is required at low concentrations. Thus in most SVE applications, thermal oxidation is not economical.

(i) The same considerations regarding the formation of dioxins apply to non-catalytic thermal oxidizers as for Cat-ox units. Though it is possible that dioxin might form as a PIC, the operating conditions of thermal oxidizers used for SVE systems are not believed to be conducive to dioxin production. At least one prominent flameless thermal oxidizer (FTO) vendor has also performed testing on its FTO system during treatment of chlorinated hydrocarbons and reports that effluent streams from its FTO system do not contain dioxins or any other significant PICs or hazardous air pollutants (www.thermatrix.com).

(j) The influent concentrations to thermal oxidizers are often expressed as the waste stream's BTU content or the percent of the waste stream's Lower Explosive Limit (LEL). The LEL is defined as the minimum concentration of chemical vapor in atmospheric air (i.e., 21% oxygen and at 20^{o}C) that is sufficient to support combustion. For safety reasons, the influent concentrations should be limited to 25% of the Lower Explosive Limit (LEL). In some industrial applications, concentrations as high as 50% of the LEL are allowed where continuous LEL monitors are in place.

(4) Scrubbers would be used in an SVE system to control acid gases generated by thermal oxidation. Scrubbers reduce acid gases and particulates in an air stream by transferring these compounds to a circulating liquid stream. For acid gas control, the pH of the liquid would be subsequently neutralized. Scrubbers are available in various configurations including venturi, spray tower, packed bed, fluidized bed, and sieve tray.

(5) The above description of a furnace-style oxidation unit can be modified in the form of a flare unit or even an internal combustion engine to oxidize the hydrocarbons. Both of these forms of oxidation can process very rich hydrocarbon streams; they are intended to operate in the explosive range, although fuel still may be added. The flare approach is rarely used in SVE or BV offgas treatment because the fixed installation costs are usually high and the influent hydrocarbon concentration is rarely high enough to justify the fixed installation cost.

Table 5-4
Comparison of VOC Control Technologies

Control Technology	Applicable Concentration Range ppm	Capacity Range L/s (cfm)	Removal Efficiency	Secondary Wastes	Advantages	Limitations
Thermal Oxidation	100-4,000	94-236,000 (200-500,000)	95-99+%	Combustion products	Up to 95% energy recovery is possible	Halogenated compounds may require additional control equipment downstream. Not recommended for batch operations.
Catalytic Oxidation	100-2,000	94-472,000 (200-100,000)	90-95%	Combustion products	Up to 70% energy recovery is possible	Thermal efficiency suffers with swings in operating conditions. Halogenated compounds may require additional control equipment downstream. Certain compounds can poison the catalyst (lead, arsenic, chlorine, sulfur, particulate matter).
Condensation	>5,000	47.2-9440 (100-20,000)	50-90%	Condensate	Product recovery can offset annual operating costs	Not recommended for material with boiling points <310°K. Condensers are subject to scale buildup, which can cause fouling.
Carbon Absorption	0-5,000	47.2-28,300 (100-60,000)	90-98%	Spent carbon; collected organic	Product recovery can offset costs. Can be used as a concentrator in conjunction with another type of control device. Works well with cyclic processes.	Relative humidity must be adjusted to <50%. Ketones and aldehydes are not efficiently adsorbed.
Resins Adsorption	500-5,000	94.4-472,000 (200-100,000)	95-98%	Wastewater; captured particulate	Product recovery can offset annual operating costs	May require special scrubbing liquids. Equilibrium data needed for design. Packing is subject to fouling and plugging, if particulates are in the gas stream. Scale formation from absorbent/absorber interaction can occur.
Biofiltration	0-1,000	47.2-236,000 (100-500,000)	90-98%	Spent peat or compost or soil. For pelletized packed bed biofilters, periodic cleaning generates wastewater with biosolids	Direct conversion of VOCs to carbon dioxide. Operates at ambient temperature and pressure. Low relative cost.	Can only be applied for biodegradable VOCs. For peat or compost or soil biofilters, the contaminated air stream has to be humidified.
Internal Combustion Engine	>4,000	24-48 (50-100)	90-98%	Combustion products	Combines vacuum pump and offgas treatment.	Requires emissions monitoring; Little additional treatment possible
Flares	>4,000	24-47,200 (50-100,000	90-98%	Combustion products	Can handle very high VOC concentrations and variations in feed rate/composition.	Substantial support equipment required; Little additional treatment possible

(6) Internal combustion engines (specifically diesel-fuel-driven engines) have been marketed to perform both the vacuum pump function and the offgas treatment. The well(s) are connected to the air inlet of the engine, which operates on a test stand to combust the hydrocarbons from the well. Diesel engines are used because they are better able to operate on a continuous basis. This approach offers competitive installed costs but is usually more difficult to permit and operate because emission monitoring must be done on the engine exhaust, and the engine can be sensitive to abrupt changes in soil vapor conditions (especially moisture).

(7) Condensation can sometimes be considered for use if the hydrocarbons are sufficiently high-boiling to be readily condensible and are present in high concentrations. While some product recovery is possible with this approach, materials which are readily condensible do not usually volatilize well at typical soil temperatures. This technology is better suited to applications where heating is used to increase the hydrocarbon removal rate from the subsurface.

(8) Biofilters have been used for odor control for industrial processes since 1953. An estimated 500 biofilters are currently in service in Europe, and 100 are in service in the United States, mainly for odor abatement. Biofiltration to reduce hazardous air pollutant emissions is a more recent development of the 1980s (Severin, Shi, and Hayes 1994). Use of biofilters to treat contaminated air streams, such as SVE offgas, is expanding due to its low cost relative to other alternatives such as thermal incineration and carbon adsorption (Govind et al. 1994; Severin, Shi, and Hayes 1994; Kosky and Neff 1988).

(a) A variety of support media have been used in biofilters, including soil, peat, compost, oyster shells, and pelletized activated carbon. A limitation of biofilters using these materials is the inability to control biomass buildup without periodically replacing the packing. Improved support media are currently being developed, for example, ceramic packing material with straight passages. Biomass periodically sloughs off from the straight passages, resulting in a self-cleaning medium.

(b) The straight passages within the support media can also have a carbon coating. This helps protect the microorganisms from shock loadings, because high contaminant concentrations will initially adsorb to the carbon, and later desorb when air phase contaminant concentrations are low (Govind et al. 1994).

c. Regulatory issues.

(1) Regulatory air emissions requirements must be considered prior to the design of the offgas control system. In some situations, air emission controls will not be necessary. Air emissions of VOCs are governed by both Federal and state regulations. Often there is a state or local limit on the concentration or total mass flow (i.e. kilograms per day) of VOC emissions. However, determining the required degree of air treatment may not be as simple as researching the applicable air discharge limit. Issues regarding media transfer and the general political climate surrounding site activities may influence the design of the offgas control system. Hazardous waste site remediation activities may be subject to more stringent requirements than other activities that result in similar emissions. For example, Massachusetts has issued a draft policy regarding offgas treatment of point-source remedial air emissions (MADEP 1993) which discusses “other considerations” on media treatment devices such as air strippers and SVE systems.

(2) Impact on cost. It should be noted that when the full cost of SVE remediation is considered, the operating cost of the offgas treatment system has significant impact on the overall cost of site remediation. Therefore, as part of the SVE design process, it is worthwhile to devote ample attention to optimizing the

offgas treatment system. This may mean developing a careful estimate of the concentrations and total mass of contaminants that may be removed from the subsurface. As discussed in paragraph 5-2*a*(4), vapor concentrations in the extracted offgas commonly decrease over time due to diffusion or partitioning rate limitations. With decreasing vapor concentrations, the cost of most thermal and catalytic oxidation systems increases, because more supplemental fuel is required. Increasing extraction rates of an increasingly dilute vapor stream serves only to exacerbate this problem. On some projects, a thermal or catalytic oxidation unit will only be needed temporarily. Thus there may be advantages to developing a contract that allows for temporary use of the off-gas treatment unit.

5-14. Summary of Condensate Treatment and Disposal Methods

a. As discussed in paragraph 5-6, condensate is typically collected because the air stream reaches 100 percent relative humidity or because water is entrained in the vapor stream. It is generally not worthwhile to construct a full-scale water treatment system merely to treat condensate collected from an SVE/BV system. Most long-term SVE/BV systems are designed not to accumulate significant amounts of condensate.

b. The following treatment and discharge methods should be considered:

- Sewer discharge.
- Surface water discharge.
- Discharge to a groundwater treatment system, if one exists.
- Storage in drums and disposal as a hazardous material.
- Discharge through activated carbon.

c. The decision will be based on the availability of these options, the concentration level of contaminants, the quantity of condensate generated, and applicable regulations. For most sites, the collected liquid will generally be disposed as a waste into some offsite facility. Before this decision is reached, there may be some onsite options which should be considered:

- Is there another liquid stream of similar concentration or source into which the condensate stream can be incorporated? This minimizes the permitting and handling problems and potential delays.
- How much solids are getting into the liquid stream? The solids may inhibit the ability to process the stream.
- Is there enough liquid generated to make processing economical? If the system generates only one drum of liquid every few months, it may be easier to dispose of the drum than to process it.
- If the condensate contains two phases, can the water phase be discharged to the sewer if the organic phase is disposed of offsite?

5-15. SVE/BV System Housing

Often SVE/BV systems will be housed in an existing building, a shed, or a trailer. If the intent is to locate the system in an existing building, there must be adequate space, electrical power, lighting, and ventilation for the system. A shed is typically constructed in situations where housing requirements are relatively minimal. SVE/BV systems are mounted to trailers for short-term projects and pilot studies when it is apparent that mobility is necessary. For BV systems involving air injection only, a doghouse or other small storage unit is sufficient housing for the blower unit.

a. There are several advantages to housing an SVE/BV system. (1) The housing protects the mechanical and electrical components from the weather. Although components may be rated as weather-proof, the system will perform more reliably and have greater longevity if protected from the weather. (2) The housing affords greater security from vandalism or unauthorized tampering. (3) A heated enclosure will reduce condensate generation and thus will also minimize the need for condensate disposal or treatment. (4) The enclosure can be designed to reduce the noise emitted from the SVE/BV system.

b. There are, however, several disadvantages to housing the system. (1) The enclosure adds to the cost and complexity of the project. (2) Without adequate ventilation, the enclosure could allow high concentrations of VOCs to accumulate to harmful or potentially explosive levels. (3) Space limitations may make operation and maintenance more difficult.

5-16. Surface Covers

a. A surface cover or impermeable cap serves two purposes. First, it minimizes infiltration of water from the surface. Infiltration water can fill soil pore spaces and reduce airflow, or fill the SVE/BV trenches if horizontal SVE/BV wells are installed. Second, a cap may also increase the radius of influence induced by the vacuum by altering the flow geometry and preventing short-circuiting of the air currents. Surface seals tend to prevent air from entering the subsurface from near the extraction well and force air to be drawn from a greater distance.

b. The most common surface cover is the use of concrete or asphalt as a cap. Many sites undergoing SVE/BV have pre-existing pavement, which may act as the surface cover. Application of a driveway sealant may be necessary to render the pavement water-resistant and to make it relatively impervious to airflow. It is important to consider that the sub-grade beneath a paved area such as a parking lot may be highly permeable sands and gravels. This high permeability layer will conduct air and eliminate the usefulness of the pavement cap. If such a sub-grade is present at a site, then it is necessary to place a barrier (e.g., using a grout or clay filled trench, similar to that shown on Figure 5-20) at the periphery of the treatment area to seal this high permeability zone from “leaking” air.

c. A synthetic lining, or geomembrane, is often used as a surface cover to eliminate water infiltration and short-circuiting. These membranes are available in a variety of materials, with high-density polyethylene (HDPE) being the most common. HDPE linings can be easily rolled out on the site and can be removed when the treatment is complete. Care must be taken to seal the membrane to any installations that penetrate it, such as vent wells, air piezometers, and monitoring wells. Geomembranes are generally a minimum of 20 mils or greater in thickness.

d. Prior to the installation of a synthetic cover, the area to be treated should be graded, smoothed, and crowned, as necessary, to eliminate any excess ponding of rainwater. If possible, the synthetic cover should then be placed over the entire contaminated area, or, in the case of a pilot study, over the expected radius of influence of the test well. Membranes are typically heat seamed. Taping, however, would be appropriate for pilot studies. Gluing is not recommended for SVE applications, because glue contains VOCs. There should be a minimum of 10 cm of overlap between sections of the surface cover. The installation procedure will vary depending on the liner used; install liners in accordance with manufacturer's recommendations. To minimize damage to the liner by personnel, equipment, or the natural elements, an appropriate (15-30 cm) thickness of fill (pulverized soil, sand, or pea gravel) can be placed over the membrane. If the membrane will be left exposed, its perimeter can be keyed into a trench and backfilled to forestall shortcircuiting of air under the liner. Keying the perimeter of an exposed membrane into a trench will not, however, prevent damage to the cover. In any case, runoff water should be directed to ditches that divert the water away from the treatment area.

e. The ability of a surface cover to prevent short-circuiting should not be over-estimated, even if it appears to be impermeable. Beckett and Huntley (1994) examined this issue at a number of sites and concluded that surface covers do not appear to act as confining layers in most cases due to imperceptible air entry paths in the surface cover, or to highly permeable base layers directly beneath the cover. Uniform vacuums at depths suggest a good surface seal and largely horizontal flow, whereas, increasing vacuum with depth suggests communication with the surface.

5-17. Design Considerations for Aboveground Soil

Many elements of designing full-scale SVE or BV systems also apply to aboveground soil pile systems. The following summarizes full-scale design elements and considerations that are likely to be unique to this soil treatment approach. Guidance for construction of an aboveground soil pile can be found in 40 CFR 264.250, Subpart L - “Waste Piles.” If a structure is to be constructed to house the soil pile, 40 CFR 264.1100, Subpart DD - “Containment Buildings,” should be consulted. Figures 3-7 and 3-8 show a typical cross-section and plan view for an aboveground soil pile.

a. Liner system. As indicated in paragraph 3-2e, aboveground soil pile treatment systems are commonly constructed on low-permeability liners to provide water/leachate drainage control. A high-density polyethylene or other synthetic liner system is best suited to a temporary remediation system, and is not well suited for long-term or repeated usage. Synthetic liner systems are typically easy to tear. For a permanent aboveground soil-pile treatment program, a more durable base, such as a concrete pad or a compacted clay overlying a HDPE liner, should be considered for design and construction. Trenches within the pad can be used to house aeration piping and gravel, thus facilitating repeated soil removal and pile construction. The liner system should have a perimeter berm to prevent run-on water from entering the treatment system as well as to keep contaminated liquids contained. A leachate collection/drainage system should be constructed to collect irrigation liquids or precipitation. The liquids may be recirculated or treated.

b. Soil placement/soil pile construction.

(1) Although overall project costs may increase due to excavation costs, construction of aboveground soil piles provides an opportunity to modify soil characteristics or facilitate the incorporation of nutrients and other amendments into impacted soils. For example, impacted soils may be processed using a mechanical shredder to eliminate clods or other heterogeneities in soil texture. Liquid nutrient applications may be made separately, or combined with the shredding operation. The addition of composting materials to impacted soils may also be considered.

(2) During aboveground soil pile construction, soil compaction should be avoided as much as possible. Use of front loaders, conveyance systems, or equivalent should be used to place soils on the lining system rather than spreading soils with grading equipment. Compaction due to equipment traffic on impacted soils will likely cause air flow anomalies such as short-circuiting, because uniform compaction in aboveground soil piles is difficult to control.

c. Aboveground soil pile geometry.

(1) An advantage of aboveground soil piles is that the system can be designed to conform to available space. Nevertheless, the following considerations should direct the final configuration and geometry of the soil pile:

- Total soil volume requiring treatment and available space.
- Soil permeability, and potential modifications to soil structure under consideration.
- Available equipment and construction options.
- Aesthetic considerations.

(2) As indicated in paragraph 3-2h, construction of aboveground soil piles can become complicated when the height of the biopile exceeds the reach of a front end loader (NEFSC 1996). For this reason it is recommended that biopile height not exceed 8 feet (2.4 m). The geometry of aboveground soil piles is that of a flat-topped pyramid having a trapezoidal cross-section. Side slopes are generally set at horizontal to vertical ratios of 1:1 to 1.5:1. The degree of side-sloping generally takes into consideration the physical properties of soil that are to undergo treatment, the duration of treatment, and whether the aboveground soil pile will be exposed or covered. Construction with a front end loader will limit the width of the biopile depending on the reach of the bucket and the height of the pile. Long, narrow piles are recommended to allow the front end loader to construct the pile by dumping contaminated soils onto the pile from either side down the length of the cell. This construction technique will keep the construction equipment from driving on the pile and compacting the soil.

(3) Generally it is recommended that aboveground soil piles be rectangular in plan. The maximum soil pile width is determined by the ability to maintain a uniform air flow along the entire length of the slotted vent screen installed in the soil pile. Further, the network of slotted pipes should be constructed to allow for flow adjustments within various segments of the pipe network. The proximity of slotted pipes to soil pile exterior surfaces must be inspected to assure that preferential or short- circuited air flow is not realized. Pipes can be placed in the pile by jacking, careful installation near the base during pile construction, or in trenches in the underlying pad. Battaglia and Morgan (1994) provide a theoretical and analytical overview of these design considerations.

(4) Generally, the air flow network manifold parallels the long dimension of the rectangular soil pile. In large soil volumes, air flow manifolds on two sides of a soil pile may be considered. The length of the biopile will depend on the volume of soil to be treated and the space availability at the site. While there are no restrictions on the length of biopiles, it is recommended that soil piles not exceed a volume of 500 yards. For sites with larger volumes of soil to be treated, additional cells should be constructed. Advantages of constructing discrete piles include ease of construction and maintenance, as well as providing the site manager with the ability to segregate soils that may have longer treatment times.

d. Aboveground soil pile covers. In comparison to other technologies addressed in this manual, design and installation of covers is unique to aboveground soil piles. Covers may be required to comply with local air pollution control district requirements to prevent volatile organic compound emissions, or to maintain favorable microclimate conditions within the soil pile. Covers can be designed to minimize stormwater infiltration into treated soils, and/or minimize/maximize thermal loss/gain. Selection of a cover should consider the candidate materials' resilience to withstand ultraviolet radiation, macroclimate conditions at the jobsite (e.g., magnitude and duration of winds), the ease of repair or replacement should tears or other mechanical damage occur, and the type of access that is necessary during system operation. If optimization of thermal gain is under consideration, clear or translucent materials are generally considered to be more effective in achieving elevated temperatures over black or opaque materials. If a geomembrane or other impermeable cover is used to cover the soil pile, a geonet drainage layers can be placed beneath the geomembrane to facilitate airflow to the entire surface area of the soil pile. Covered aboveground soil piles have often included structural supports to suspend the cover above the soil pile rather than allowing it to rest on the soil pile surface. The intent is to maintain uniform air entry into the soil pile. The advantages/disadvantages of alternative support systems are unclear. Geomembranes are somewhat difficult to work with due to their thickness. Lighter alternatives exist, including polyester-filament reinforced polyethylene sheeting. These have strength adequate to withstand wind conditions over the typical duration of biopile use.

5-18. Process Safety Review

a. Process Safety Review/HAZOP review. A formal Hazard and Operability (HAZOP) review of the system and its integration with other systems (designed and supplied by others) may be required. The review shall consider each unit operation and possible hazards, and operations and maintenance difficulties that might occur. All findings shall be recorded and a formal response prepared. Figure 5-25 is a sample Process Hazard Review form. The review should be held no later than 30 calendar days before the start of the SVE/BV system operation, and all deficiencies should be corrected prior to system startup.

b. HAZOP study. A HAZOP study is defined as the application of a formal systematic detailed examination of the process and engineering intention of new or existing facilities to assess the hazard potential of operation outside the design intention or malfunction of individual items of equipment and their consequential effects on the facility as a whole.

c. Guide words. During examination sessions the study team tries to visualize all possible deviations from every design and operating intention. These deviations, each of which can be associated with a word or phrase, are called “guide words” because when used in association with a design and operating intention

PROCESS HAZARD REVIEW

DATE ___________

PROJECT: ______________________

Review NO.

GUIDE WORD/VARIABLE: __________________________
e.g. Hi/Level

INTENTION/LOCATION:

CAUSE/CONSEQUENCE:

ACTION BY: ________________________________

QUESTION OR ACTION RECOMMENDED:

RESPONSE:

Figure 5-25. Sample process hazard review (HAZOP).

they guide and stimulate creative thinking toward appropriate deviations. The following is a list of deviations and associated guide words:

NO FLOW:	Wrong routing - blockage - incorrect slip blind - incorrectly installed check valve - burst pipe - large leak - equipment failure (control valve, isolation valve, pump, vessel, etc.) -incorrect pressure differential - isolation in error.
REVERSE FLOW:	Defective check valve - siphon effect - incorrect differential pressure - two-way flow - emergency venting - incorrect operation - in-line spare equipment.
MORE FLOW:	Increased pumping capacity - increased suction pressure - reduced delivery head - greater fluid density - exchanger tube leaks - restriction orifice plates deleted - cross connection of systems - control faults - control valve trim changed.
LESS FLOW:	Line restriction - filter blockage - defective pumps - fouling of vessels, valves, orifice plates - density or viscosity changes.
MORE LEVEL:	Outlet isolated or blocked - inflow greater than outflow - control failure - faulty level measurement.
LESS LEVEL:	Inlet flow stops - leak - outflow greater then inflow - control failure - faulty level measurement.
MORE PRESSURE:	Surge problems - leakage from inter-connected HP system - gas breakthrough (inadequate venting)- isolation procedures for relief valves defective - thermal overpressure - positive displacement pumps - failed open PCVs - design pressures - specification of pipes, vessels, fittings, instruments.
LESS PRESSURE:	Generation of vacuum condition - condensation - gas dissolving in liquid -restricted pump/compressor suction line - undetected leakage - vessel drainage - blockage of blanket gas reducing valve.
MORE TEMPERATURE:	Ambient conditions - fouled or failed exchanger tubes - fire situation - cooling water failure - defective control - heater control failure - internal fires - reaction control failures - heating medium leak into process.
LESS TEMPERATURE:	Ambient conditions - reducing pressure - fouled or failed exchanger tubes - loss of heating - depressurization of liquified gas - Joule/Thompson effect.

MORE VISCOSITY: Incorrect material specification - incorrect temperature - high solids concentration.

LESS VISCOSITY: Incorrect material specification - incorrect temperature - solvent flushing.

COMPOSITION CHANGE: Leaking isolation valves - leaking exchanger tubes - phase change - incorrect feedstock/specification - inadequate quality control - process control upset - reaction intermediates/byproducts - settling of slurries.

CONTAMINATION: Leaking exchanger tubes or isolation- incorrect operation of system- interconnected systems (especially services, blanket systems) - effect of corrosion - wrong additives - ingress of air shutdown and startup conditions.

RELIEF: Relief philosophy (process/fire, etc.) - type of relief device and reliability - relief valve discharge location - pollution implications - two-phase flow - effect of debottlenecking on relief capacity.

INSTRUMENTATION: Control philosophy - location of instruments - response time - set points of alarms and trips - performance check points - sampling ports - time available for operator intervention - alarm and trip testing - fire protection - trip/control amplifier - panel arrangement and location - auto/manual facility and human error - fail safe philosophy;

SAMPLING: Sampling procedure - time for analysis result - calibration of automatic samplers - reliability/accuracy of representative sample - diagnosis of result.

CORROSION/EROSION: Cathodic protection arrangements internal/external corrosion protection engineering -specifications - embrittlement - stress corrosion cracking - fluid velocities.

SERVICE FAILURE: Failure of instrument air/stream/nitrogen/cooling water/hydraulic power/electric power/water or other - contamination of instrument air, nitrogen, etc. - telecommunications - heating and ventilating systems - computers.

ABNORMAL OPERATION: Purging - flushing - startup - normal shutdown - emergency shutdown - emergency operations.

MAINTE- NANCE:	Isolation philosophy - drainage - purging - cleaning - drying - blinding - access - rescue plan - training - pressure testing - work permit system - condition monitoring.
IGNITION:	Grounding arrangements - insulated vessels/equipment - low conductance fluids - splash filling of vessels - insulated strainers and valve components - dust generating and handling - hoses - hot surfaces.
SPARE EQUIPMENT	Installed/non-installed spare equipment - availability of spares - modified specification - storage of spares - catalog of spares, etc. - test running of spare equipment.
SAFETY:	Toxic properties of process materials - fire and gas detection system/alarms - emergency shutdown arrangements - fire fighting response time - emergency and major emergency training - contingency plans - TLVs of process materials and methods of detection - first aid/medical resources - effluent disposal - hazards created by others (adjacent storage areas/process plant, etc.) - testing of emergency equipment - compliance with local/national regulations.

5-19. Examples of SVE/BV System Designs

a. The major SVE/BV components have been individually discussed in paragraphs 5-3 through 5-16. This section will demonstrate, by example, the interrelationship among components. In this section, a hypothetical site will be considered and a sample preliminary SVE design will be established. Actual SVE systems can be designed in innumerable ways based on site conditions, contaminant properties and concentrations, project duration, and customer preference.

b. This section will acquaint the reader with design documents. See Chapter 6 for a more detailed discussion of design documents.

(1) Site layout.

(a) A sample site plan is shown in Figure 5-26. The site plan shows the location of major site components and helps address the following issues:

- Treatment system location.
- Well and piezometer locations.
- Location of buried piping.
- Road access.

- Site grading for drainage.

- Electrical hook-up location.

- Gas hook-up.

(b) As discussed in paragraph 5-2, the locations of the vapor extraction wells are of great significance to the overall design, and depend on many factors including nature and extent of contamination, soil characteristics, and air permeability. In this example, the wells were placed within the zone of high contaminant concentrations to maximize removal rates. Air piezometers were located at increasing distances from the vapor extraction wells in several directions. This example illustrates that site drainage is particularly important if an impermeable liner is placed on the site as incorrect grading will cause ponding. Also, it is important to be aware of the location of utilities both for the purpose of accessing them for the treatment system and to avoid damaging them during subsurface work. Typically, the mechanical details of the treatment system are not shown on these drawings, depending on the scale of the treatment system relative to the site.

(2) Process design.

(a) A typical preliminary SVE Piping and Instrumentation (P&I) diagram is shown in Figure 5-27. In this example, soil vapor is extracted from four wells. The well layout resulted from data collection during predesign testing and subsequent modeling of airflow streamlines to arrive at an effective radius of influence at which an acceptable velocity was predicted. In the resulting design, the flow converges at an inlet manifold where flow is controlled and pressure is monitored. The vapor stream progresses through an air/water separator, inlet filter, inlet silencer, blower, outlet silencer, and either vapor phase carbon or catalytic incineration. All these components have been described in detail in previous sections. Process controls and instrumentation, such as gauges, valves, and indicators are also shown.

(b) This sample process design demonstrates several features of typical SVE systems that may not have been emphasized in previous sections. These features include:

- Vapor sampling ports which are necessary to assess the progress of the remediation and the effectiveness of offgas treatment.

- An ambient air intake to be used during start-up, shutdown, and to dilute the air stream, if necessary.

- Temperature controls to avoid overheating the blower.

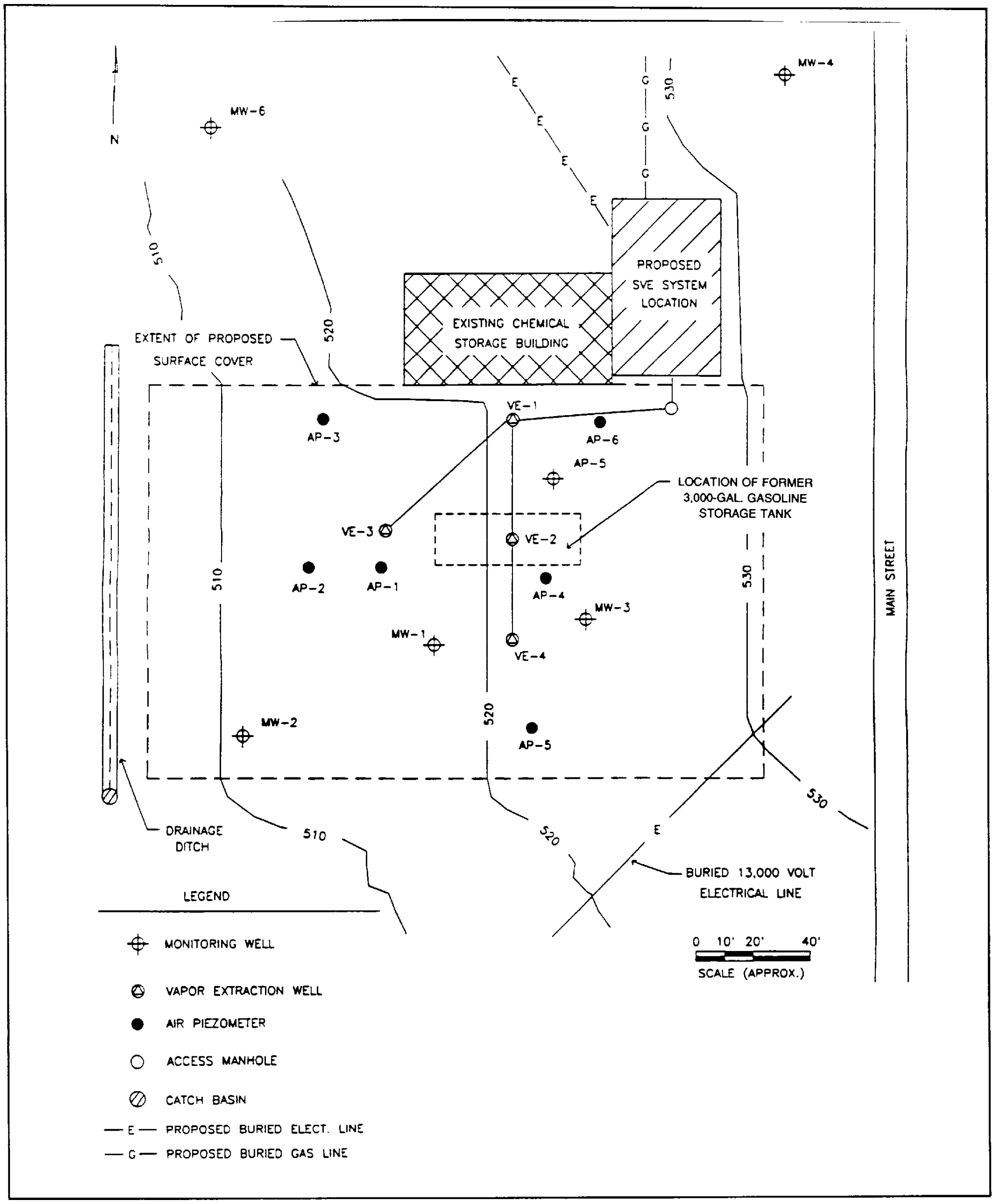


Figure 5-26. Typical SVE site plan.

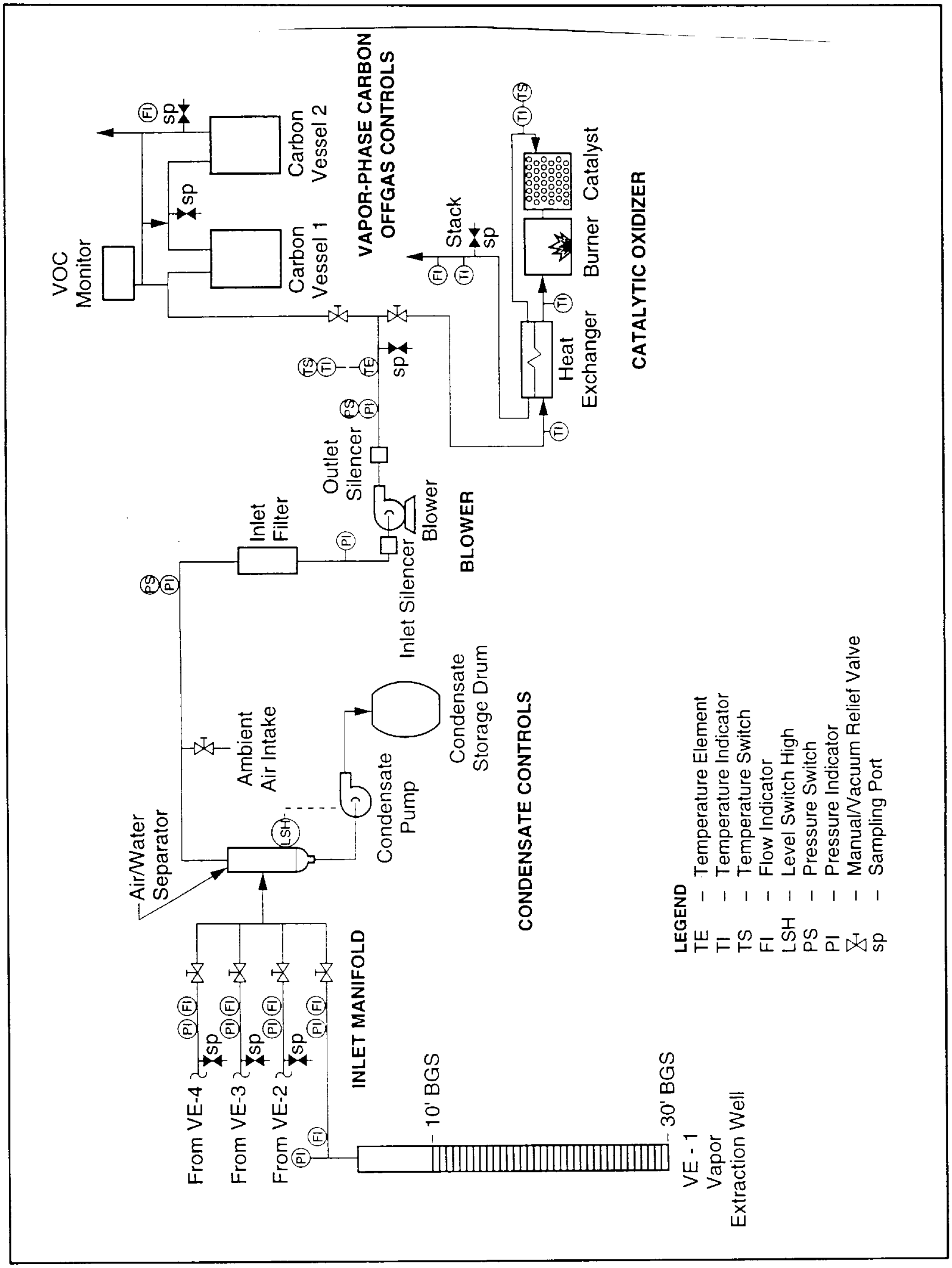


Figure 5-27. Typical SVE preliminary P&I diagram.

(c) This design shows both vapor-phase carbon and catalytic incineration mainly for illustrative purposes. However, it may not be unreasonable to include both forms of control in some situations. The contaminant concentration will decrease with time and catalytic oxidation, relative to carbon, is more cost effective for the initially concentrated vapor streams. For example, it may be economical to lease a catalytic incinerator for the first several months of a project and utilize carbon for the remainder of the project.

(3) Mechanical design.

(a) A mechanical layout shows all treatment system components drawn to scale and dimensioned. Particular detail is devoted to components requiring onsite construction and installation. Less detail is devoted to vendor-supplied components. For example, the blowers are merely drawn to the appropriate dimensions and located; complete mechanical details can be obtained from the manufacturer. To retain clarity at the scale of the drawing, all piping below a certain nominal size should be shown schematically and not drawn to scale.

(b) To minimize the distances of interconnected piping and wiring, the general layout typically follows from the Process Flow Diagram. The mechanical design must allow the components to be easily installed and maintained. System controls, particularly alarms, must be visible. For SVE systems mounted on skids or trailers, the mechanical designer must pay close attention to the weight distribution of the components.

(4) Electrical design.

(a) The electrical design must incorporate the power requirements and the process controls. The process controls shown in this example are electrical but they could also be pneumatic. Figure 5-28 illustrates a typical electrical schematic for an SVE system.

(b) In this example, a 460-volt, three-phase, three-wire hookup is supplied to the system. The blower motor and the catalyst main control panel will operate off of the 460-volt, three-phase power. The remainder of the electrical controls will operate with single-phase 115-volt power that is achieved with a transformer. This example assumes that the vendor-supplied catalytic incinerator comes complete with its own controls, and the controls would not be designed by the engineer. The 115-volt electrical controls are shown in typical ladder logic format. Notice that the blower can be shut off by any of the following three conditions: (1) high water level in the condensate tank, (2) high pressure at the blower, or (3) high temperature at the blower outlet. A separate electrical hookup is provided for the utility outlet, a fluorescent light, and the VOC meter power supply. This allows the SVE system to be shut down without impacting these components.

(c) Logic diagram. A logic diagram shall be included as part of the electrical control design, if needed for clarification.

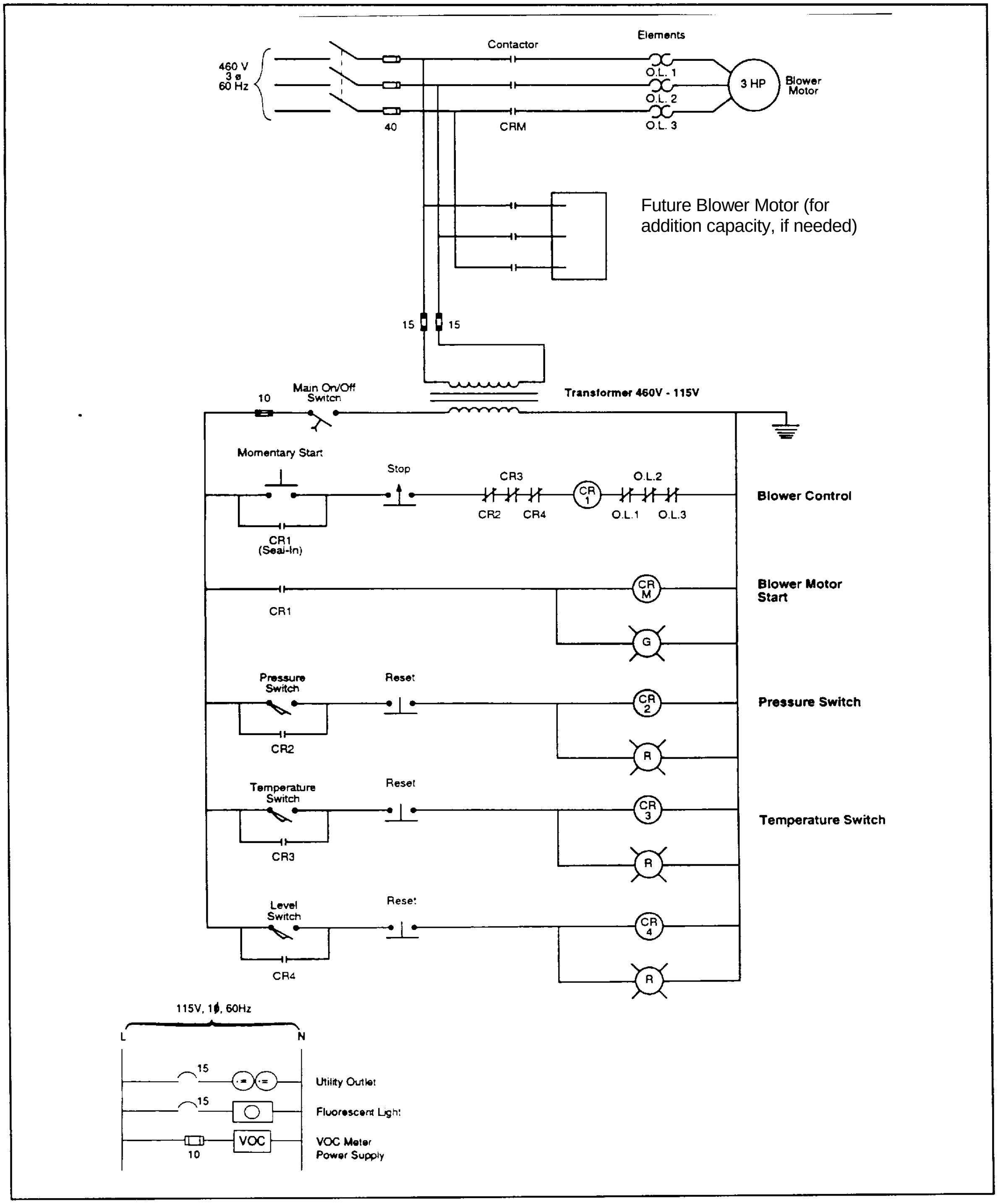


Figure 5-28. Typical SVE electrical schematic.